SATCOM

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The Direct Broadcast Satellite–Radio Program

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NASA's commitment to achieving new commercial applications for communications satellite technologies is reflected in the Direct Broadcast Satellite–Radio (DBS–R) program, a three-year, $2.5 million program established in May 1990 by interagency agreement between NASA and the United States Information Agency/Voice of America (VOA). NASA's contributions to this program, which is designed to provide service and technology definition and development for direct-to-listener satellite sound broadcasting, reflect the combined efforts of the Lewis Research Center, NASA's lead center for commercial communications, and the Jet Propulsion Laboratory, where research in mobile, micro and personal communications is conducted under the SATCOM Program. These efforts are accomplished with the support of NASA's Office of Commercial Programs.

A direct-to-listener satellite radio broadcasting service has been discussed within the international telecommunications community for many years [1–9]. Recent developments in digital and mobile communications satellite and receiver technologies, however, have greatly broadened the possibilities of such a service far beyond those originally expected. It is now envisioned that listeners will be able to obtain radio broadcasts in a variety of environments (indoor/outdoor, rural/urban, mobile/stationary) at a variety of levels of sound quality — ranging from robust AM quality to compact disc quality — via digital transmission at a variety of data rates [10,11]. As a consequence of both substantial discussion over a period of years in the international telecommunications community and rapid technological developments, member nations of the International Telecommunications Union will consider a frequency allocation to the Broadcast Satellite Service (BSS) (Sound) in the range of 500–3000 MHz at the 1992 World Administrative Radio Conference (WARC), which is a critical milestone in enabling implementation of the service [12].

Direct broadcasting of sound by satellite offers a number of potential benefits to listeners. Perhaps the most important of these is that wide-area coverage achieved via satellite broadcasting will present new opportunities for audience access to programming — particularly educational, cultural

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The Satellite Communications (SATCOM) Program is managed by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. The goals of this Program are to develop advanced system concepts and technologies in the areas of mobile, micro and personal communications. A major thrust of the Program through the mid-1990s is the development of the mobile terminal to operate with NASA's Advanced Communications Technology Satellite.

or target-audience oriented — that may not be economically attractive to offer in any other way. The potential benefits of establishing a satellite sound broadcasting service have attracted the attention of a number of commercial communications companies interested in providing this service on either a domestic or international basis, and the attention of both national and international organizations engaged in development of broadcast programming [13].

Service and Technology Definition and Development for DBS–R

NASA's DBS–R program is designed to benefit the U.S. commercial communications satellite industry — and future DBS–R system users — via a structured program of service and technology definition and development. Program management is provided by the Communications Systems Branch in the Space Electronics Division of the Lewis Research Center. Efforts are focused on system definition, satellite experimentation and demonstration, propagation measurements, receiver development, market and organization studies, legal and regulatory studies and preparations for WARC 1992.

DBS–R System Trade-Offs

The Jet Propulsion Laboratory is performing technical trade-off analyses to examine effects of various factors determining potential DBS–R system parameters. The system study effort has explored various audio coding methods to identify a correspondence between the digital bit rate and audio quality. Rates from 16 to 32 kbps are identified with AM quality; 48 to 64 kbps may provide monophonic FM quality; 96 to 128 kbps will provide stereophonic FM quality; compact disc quality sound may be provided at 192 to 256 kbps. Exploration of a range of digital bit rates and a corresponding range in sound quality arises from the recognition that a number of important user needs, such as receiving news, disaster warnings and educational/cultural programming, may be accomplished at less than CD quality and at a correspondingly lower cost. The system study has characterized the effect of frequency on DBS–R satellite RF power requirements, size and cost utilizing a model originally developed for MSAT studies and modified for DBS–R to accommodate variations in frequency, beam size, number of satellite beams, number of programs, link margin and program quality. Results indicate that within selected portions in the range of 500–3000 MHz, the DBS–R satellite will become either weight or power limited, with corresponding increases in space segment cost. The system study has also contributed significantly to the development of DBS–R receiver requirements [11].

Satellite Experiment and Demonstration

This winter, NASA hopes to provide a demonstration of satellite sound broadcasting to a moving vehicle in the Washington, D.C., area. This demonstration is likely to be the first in the world to incorporate the satellite link in a live demonstration of sound broadcasting with mobile reception. During the month of September, several weeks of experimentation utilizing satellite capacity provided by INMARSAT, uplinking from the COMSAT Earth station facility in Southbury, Connecticut, were conducted to lay the groundwork for the demonstration. Experimental measurements will provide valuable definition of interleaving requirements for DBS–R receivers and will further characterize the DBS–R mobile reception environment. NASA hopes to demonstrate the technical feasibility of the DBS–R concept to a number of invited participants, using demonstration programming provided by National Public Radio. Building on technology developed in its land mobile satellite research program, the Jet Propulsion Laboratory is concluding preparation of the experimental system for this end-to-end demonstration of satellite sound broadcasting to a mobile receiver.

Propagation Measurements

Through its ongoing propagation program at the Jet Propulsion Laboratory, NASA is sponsoring research by the University of Texas designed to characterize the propagation environment for DBS–R. Research objectives include determining spatial, temporal and spectral variations of signals within the environment of various structures and determining the degree of building penetration

losses affecting indoor DBS–R reception. Measurements are being made in the 800–1800-MHz range of the spectrum and are extrapolated to an upper limit of 3000 MHz. Thus far, the research has revealed that indoor signal levels exhibit significant spatial and spectral structure; signal amplitude troughs of several dB, with widths up to 30 MHz in frequency and spatial distances up to 30 cm, were observed within a variety of building types. An important implication of these findings is that small-scale antenna diversity in the DBS–R receiver may be a realistic approach to mitigating signal impairment in the indoor environment [14].

Receiver Development

The VOA is sponsoring efforts by the Jet Propulsion Laboratory to develop a low-cost DBS–R receiver capable of accommodating a range of digital bit rates. Thus far, the results of system definition studies and propagation research have been applied to defining fixed and portable receiver requirements. Selectable data rates of 32, 64, 128 and 256 kbps, and hence selectable sound quality, will be implemented. A frequency division multiplexed signal with power and bandwidth efficient coding and modulation will be accommodated for different rate audio channels. Rate 1/2, constraint length 7 convolutional coding will be implemented, providing a powerful method of error correction and contributing to design simplicity due to the fact that the decoder is available on a single chip. Low cost and design simplicity are goals of the development effort, which is directed toward design and implementation of a receiver prototype that is as close as possible to a readily producible model. Receiver design will be modular in order that enhancements such as antenna diversity can be added to the receiver's core capability without requiring redesign [15].

Market/Organization Studies

Lewis Research Center, with Contel Federal Systems, has explored market and organizational aspects of DBS–R system implementation — such as the demand for higher levels of sound quality and the cost-effectiveness of various levels of system capacity and sound quality. A transition to audio media of higher dependability and quality is evidenced on a worldwide basis. The design of the DBS–R space segment will depend both on the capacity to be offered and the operating frequency band(s), which will directly determine spacecraft antenna size and power requirements. A system offering a range of audio quality selections would provide the greatest flexibility in meeting DBS–R user needs. While a lower capacity spacecraft is costlier to operate on a per-channel basis, it has the advantage of requiring a lower initial investment and shorter construction time and therefore may be attractive from a business perspective. The technology necessary to provide the space segment will largely be an extension of that developed for mobile satellite services; the greatest technological challenge is represented by the development of DBS–R receivers, due to the fact that the DBS–R signal is subject to degradation by interruptions in the line of sight from satellite to receiver introduced by buildings, tunnels or foliage. It is predicted, however, that receivers may be developed at costs ranging from $100 to $300 per unit that will provide for DBS–R reception on a mobile, fixed or portable basis [16].

The VOA is sponsoring efforts by JPL to develop a low-cost DBS–R receiver capable of accommodating a range of digital bit rates.

Legal/Regulatory Studies

Lewis Research Center, again with Contel Federal Systems, has examined domestic and international legal and regulatory considerations affect-

ing establishment of a DBS–R service. Implementation of DBS–R may take place in a variety of ways, depending in part upon the legal and regulatory environment encountered. In the United States, which is one of the few nations that permits private commercial organizations to operate communications satellites, one or more petitioners to the Federal Communications Commission (which regulates commercial usage of the radio frequency spectrum in the United States) would require a license to provide such a service. There are several similarities between DBS–R and mobile satellite services; thus, it is possible that DBS–R will be regulated, in many ways, like the MSS. In particular, since DBS–R will serve omnidirectional antennas for mobile reception, frequency reuse among different DBS–R systems will require careful coordination. Therefore, the total number of DBS–R licensees will depend in part upon the total amount of spectrum made available for DBS–R. A major conclusion of this study is that systems which are commercially financed and operated, and subscribe to common internationally established technical guidelines, offer the best prospects for establishing DBS–R systems within the domestic and international marketplace. Results of the study have met with substantial attention on the part of U.S. and international DBS–R commercial communications interests, particularly within Europe, as the European Community nations have begun to explore regulatory restructuring of satellite communications systems. While a number of complex regulatory issues remain to be resolved, findings are encouraging with respect to opportunities for the U.S. satellite communications industry to participate in the offering of a new service in the domestic sphere and, perhaps, in new spheres abroad [16].

DBS–R systems that are commercially financed and operated, and subscribe to common internationally established technical guidelines, have the best possibility of being established within the domestic and international marketplace.

Preparations for WARC 1992

Building on previous national and international spectrum/orbit utilization activities for a variety of commercial communications satellite services, NASA's Office of Commercial Programs and the Lewis Research Center are engaged in providing technical contributions to both U.S. and international preparations for WARC 1992, which will consider a frequency allocation to the BSS (Sound). A frequency allocation is necessary to permit eventual implementation of a DBS–R service.

The International Telecommunications Union, an organization within the United Nations, convenes periodic Administrative Radio Conferences to construct agreements among member nations on the use of the radio frequency spectrum, which is a limited resource. The World Administrative Radio Conference for Dealing With Frequency Allocations in Certain Parts of the Spectrum will be held February 3 through March 3, 1992, in Malaga/Torremolinos, Spain. This Conference will consider a frequency allocation to the BSS (Sound) service in the range of 500–3000 MHz under Agenda item 2.2.3(a). A number of domestic and international activities are underway in preparation for the Conference; NASA has been an active participant in these activities, fulfilling a statutory role in assisting the U.S. satellite communications industry by providing technical expertise to the WARC preparatory process.

Within the United States, Conference preparations are under way on the part of the Department of State, the Federal Communications Commission and the National Telecommunications and Informa-

tion Administration, with the participation of NASA, other government agencies and industry. Currently, the United States is in the process of determining its position on a proposed allocation to the BSS (Sound) service. While it is agreed that an allocation to BSS (Sound) is appropriate, the proposed allocation's location within the spectrum is a very complex issue to resolve. The 500–3000-MHz portion of the spectrum is heavily utilized by a number of diverse communications services; it is difficult to locate a portion of the spectrum in which both existing services and the BSS (Sound) service can operate successfully. A number of options for a BSS (Sound) frequency allocation are currently under consideration.

On an international basis, a number of organizations are also preparing for the WARC. The International Radio Consultative Committee (CCIR) provides the technical basis for the consideration of decisions at the Conference. CCIR Joint Interim Working Party 10-11/1, which met last year in Sydney, Australia, provided technical input on the issue of BSS (Sound) to the Joint Interim Working Party WARC-92, which met in Geneva this year to finalize the technical basis for WARC 1992. NASA contributed six of a total of nine U.S. inputs on the subject of the BSS (Sound) to CCIR JIWP 10-11/1 and all U.S. inputs on this topic to JIWP WARC-92 [17–25]. The telecommunications committee of the Organization of American States (CITEL) has also considered BSS (Sound); NASA has also contributed to position and technical seminar papers on BSS (Sound) for CITEL and has provided a spokesperson for this issue in the U.S. CITEL delegation.

NASA's DBS–R WARC preparatory effort, as led by Lewis Research Center with contributions from the Jet Propulsion Laboratory, has provided substantial technical contributions to both domestic and international consideration of the optimal frequency allocation for the BSS (Sound). As WARC 1992 approaches, NASA will continue to participate in U.S. and international Conference preparations on both the issue of a frequency allocation to the BSS (Sound) service and establishing a General Satellite Service at 20/30 GHz.

Conclusion

The NASA/VOA DBS–R program is designed to assist in creating opportunities for the U.S. satellite communications industry to provide a new service that will give a number of important benefits to its users. The program represents a focused effort to provide service and technology definition and development for DBS–R. Since the DBS–R program's inception in May 1990, NASA's Office of Commercial Programs, the Lewis Research Center and the Jet Propulsion Laboratory have achieved significant contributions in the development of a DBS–R service. In the months to come, the satellite demonstration, receiver development effort and WARC 1992 will provide further opportunities for NASA to contribute to making the benefits of a DBS–R service a reality.

References

[1] Resolution No. 520 of the 1988 World Administrative Radio Conference.

[2] Resolution No. 505 of the 1979 World Administrative Radio Conference.

[3] *Voice Broadcast Mission Study, Volumes I and II — Study Report*, General Electric Missile and Space Division, under NASA LeRC Contract NAS W-1475, July 1967.

[4] *Voice Broadcast Mission Study*, RCA Astro-Electronics, under NASA LeRC Contract NAS W-1476, July 1967.

[5] M. Horstein, *Satellite Voice Broadcast System Study, Volume II — Technical Report*, TRW Inc., under NASA LeRC Contract NAS3-24232, NASA Contractor Report CR 174905, July 1985.

[6] E. E. Bachtell, et al., *Satellite Voice Broadcast System Study*, Martin Marietta Denver Aerospace, under NASA LeRC Contract NAS3-24233, August 1985.

[7] G. Stevens and C. Provencher, *Sound Broadcasting by Satellite: A NASA Assessment for the Voice of America*, NASA Lewis Research Center, January 31, 1986.

[8] *Antennas, Satellite Broadcasting and Emergency Preparedness for the Voice of America*, prepared by the Committee on Antennas, Satellite Broadcasting and Emergency Preparedness for the Voice of America, Board on Telecommunications and Computer Applications, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, D.C., 1988.

[9] G. H. Stevens and R. L. Spence, *Complementary Satellite Sound Broadcasting Systems — A NASA Assessment for the Voice of America*, NASA Lewis Research Center, January 1988.

[10] *Report to JIWP WARC-92 on Satellite Sound Broadcasting for Portable and Vehicle Receivers*, CCIR Joint Interim Working Party 10-11/1, Document JIWP 10-11/1-62E, November 28, 1990.

[11] N. Golshan, *Direct Broadcast Satellite–Radio: Systems Tradeoffs Study, Interim Report*, JPL Internal Document D-8615, June 1991.

[12] Agenda (Resolution No. 995), World Administrative Radio Conference for Dealing With Frequency Allocations in Certain Parts of the Spectrum, adopted by the ITU Administrative Council, 45th Ordinary Session, June 11–22, 1990.

[13] Federal Communications Commission, Second Notice of Inquiry Relating to Preparation for the International Telecommunication Union World Administrative Radio Conference for Dealing With Frequency Allocations in Certain Parts of the Spectrum, Gen. Docket No. 89-554.

[14] Jet Propulsion Laboratory, "Direct Broadcast Satellite–Radio: Propagation Measurements," presentation, DBS–R Program Review, July 1991.

[15] *Draft Functional Requirements, DBS–Radio Receiver*, Version 91-A, JPL Internal Document, July 1991.

[16] D. R. Sood, et al., *Direct Broadcast Satellite–Radio: Market, Legal, Regulatory and Business Considerations — Summary*, Contel Federal Systems Government Networks Group, NASA Report No. CR-187093, March 1991.

[17] A. O. Heyward, *Conclusions Regarding Frequency Sharing With the Satellite Sound Broadcasting Service in the Range 500–3000 MHz*, Document No. JIWP 10-11/1-030, November 1990.

[18] A. O. Heyward, *The Impact of Frequency on the Sound Broadcasting Satellite*, Document No. JIWP 10-11/1-032, November 1990.

[19] A. O. Heyward, *Analysis of Frequency Sharing Possibilities With the Satellite Sound Broadcasting Service*, Document No. JIWP 10-11/1-033, November 1990.

[20] N. Golshan and A. Vaisnys, *Satellite Sound Broadcasting to Portable Receivers*, Document JIWP 10-11/1-025, November 1990.

[21] N. Golshan, *Satellite Sound Broadcasting to Vehicular Receivers*, Document No. JIWP 10-11/1-026, November 1990.

[22] W. J. Vogel and J. Kiebler, *Propagation Impairment Criteria for Satellite Sound Broadcasting in the Frequency Range 500 MHz to 3 GHz*, Document No. JIWP 10-11/1-029, November 1990.

[23] A. O. Heyward, *Interference to BSS (Sound) Reception From Industrial, Scientific and Medical Emissions in the Band 2400–2500 MHz*, Document No. JIWP WARC92-57, March 1991.

[24] N. Golshan and A. Vaisnys, *Service Objectives for Satellite Sound Broadcasting*, Document JIWP WARC92-59, March 1991.

[25] W. J. Vogel and J. Kiebler, *Results of U.S. Propagation Measurements BSS (Sound) Since JIWP 10-11/1*, Document No. JIWP WARC92-58, March 1991.

Direct Broadcast Satellite–Radio System Trade-Off Study

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There has been considerable international effort in the areas of system studies, system development and regulatory work toward a Direct Broadcast Satellite–Radio (DBS–R) system [1–5]. An important milestone will be the 1992 World Administrative Radio Conference (WARC), where consideration will be given to frequency allocation in the 500–3000-MHz range for such a service.

There is an interagency agreement between VOA and NASA for a coordinated program on DBS–R. This program includes seven tasks: Systems Trade-Off Studies, Propagation Measurements, Satellite Experiment and Demonstration, Receiver Development, Market Studies, Regulatory Studies and WARC Preparations. This article reports on some findings of the first task [4].

Digital Bit Rate and Audio Quality for DBS–R

Considerable work has been done and progress has been made in digital coding of 20-kHz audio due to ISO (International Standards Organization) activity toward achieving bit rates under 256 kbps for compact disc (CD) quality stereo music. Systems developed toward these objectives use either sub-band or transform coding and rely on the noise masking threshold of the human auditory system for efficient adaptive bit allocation schemes [6–9]. With these technologies, digital coding of music is feasible at bit rates in the range of 192 to 256 kbps.

One can significantly reduce the required bit rate by choosing a monophonic system, allowing degradation of the audio quality in bandwidth or dynamic range, or both. Based on the status of audio coding technology, the following grades of audio quality and bit rates have been identified for DBS–R applications [4]:

- Digital broadcasting of monophonic audio with bit rates in the 16–32-kbps range with subjective audio quality comparable to AM broadcasting.
- Digital broadcasting of monophonic audio with bit rates in the 48–64-kbps range with subjective audio quality comparable to monophonic FM broadcasting.
- Digital broadcasting of stereophonic audio with bit rates in the 96–128-kbps range with subjective audio quality comparable to stereophonic FM broadcasting.
- High-fidelity digital stereo broadcasting at bit rates in the 192–256-kbps range with subjective quality approaching that of CDs.

Propagation Considerations and Link Margin Estimates for Portable Reception

The University of Texas at Austin performed DBS–R propagation experiments over the frequency range of 700 to 1800 MHz inside six buildings of various types and construction material. The results indicate strong spatial and spectral signal variations inside buildings [10]. The results may be summarized as follows:

- The indoor signal levels were found to have much spatial and spectral structure but were relatively stable in time.
- When the signal level is displayed jointly as a function of frequency and spatial disablement, amplitude troughs of several dB are observed. The widths of such amplitude troughs are typically 5–30 MHz in the frequency domain and 10–30 cm in the spatial dimension. Both trough-to-crest distances (40 cm) and trough lengths (10–30 cm for thresholds from –18 to –3 dB) varied little from building to building and were insensitive to the direction of measurement. The short distances (10–30 cm) out of a frequency/spatial trough should make small-scale antenna diversity reception feasible.

- Amplitudes in a given frequency span were found to disperse with the logarithm of the bandwidth. Within bandwidths below about 1 MHz, signal levels were nearly constant, signifying that there were neither very narrow absorption features nor very long multipath delays. Multipath delays of 50 ns were observed in only one of the buildings. Coherence properties, such as distortion and trough frequency widths, were discovered not to be a function of frequency.
- Of all the parameters that were measured, only building attenuation showed a clear frequency dependence.
- Attenuation, which at an average position in a room increased from 6 to 12 dB over the range of 750 to 1750 MHz, could be mitigated by 2 to 6 dB by moving the antenna — by less than 30 cm in most cases. The most severe losses (17.5 dB, mitigated to 12.5 dB) were observed in a concrete wall building; the longest multipath delays (greater than 100 ns) were found in the same building. Large losses observed in the most difficult buildings (concrete building, mobile home and metal shack) could be reduced to a few dBs by moving the receiver antenna close to a window exposed to the transmitter.

Based on the DBS–R propagation measurements at the University of Texas [10] and the ATS-6 experiments [11], link margin requirements have been estimated for portable DBS–R reception as a function of frequency for three levels of severity of shadowing [4]. The results are given in Figure 1. The results are valid for satellite elevation angles in the range of 30 to 60 deg.

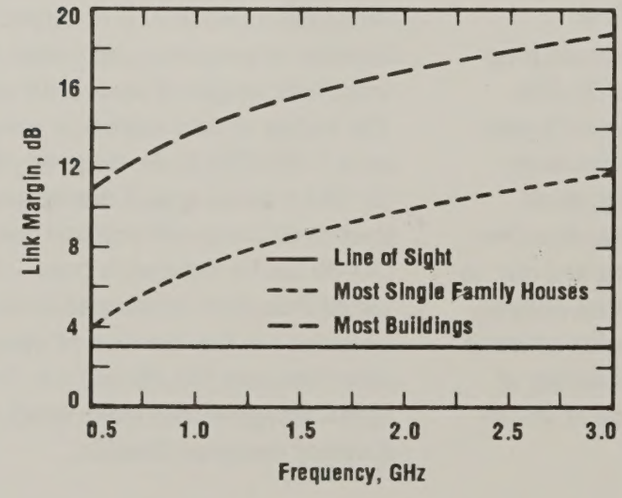

Figure 1. DBS–R link margin, portable reception.

Link Margin Estimates for Mobile Reception

There is a significant body of experimental, theoretical and modeling work on the Land Mobile Satellite Service (LMSS) channel. Available information includes experimental data obtained with the ATS-6, MARECS and ETS satellites, as well as a number of terrestrial simulations of the LMSS channel using balloons, towers and aircraft [13–25].

The most severe losses were observed in a concrete building; the longest multipath delays were found in the same building.

Figure 2 provides the typical link margin requirements for mobile reception of DBS–R as a function of frequency for three levels of severity of shadowing [4].

The large link margins shown for heavy urban shadowing can be avoided by the use of terrestrial boosters. Short-term signal blockage in rural and suburban areas can be mitigated by diversity techniques without a need for terrestrial retransmission.

Typical DBS–R Link Budgets

Table 1 gives a typical DBS–R link budget for mobile and indoor portable reception of one CD-quality program at a nominal frequency of 1.5 GHz over the range of a 3-deg spot beam. Tables 2A and 2B provide a summary of portable and mobile DBS–R link parameters for three choices of frequency (0.75, 1.5 and 2.4 GHz), two choices of spot beam size (3 deg and 1 deg) and two choices of audio quality (monophonic FM-quality digital audio at 48 kbps and CD-quality stereophonic audio at 256 kbps). The tables are based on the following assumptions:

- For table-top portable reception at 0.75 GHz, a nearly omnidirectional receiver antenna with a gain of 5 dBi is assumed. Higher gains of 8 and 12 dBi are assumed for the receiver antenna at the frequencies of 1.5 and 2.4 GHz, corresponding to an effective aperture of 380 sq cm (0.42 sq ft).
- For mobile reception, an omnidirectional antenna with a gain of 5 dBi is assumed at all three frequencies to avoid tracking requirements at the receiver.

Audio link budget	Portable reception		Mobile reception	
	Mean	Tolerance (±)	Mean	Tolerance (±)
Information bit rate/program, kbps	256.00		256.00	
Transmitter power per program, W	25.50		25.50	
Transmitter power per program, dBW	14.07		14.07	
Frequency, GHz	1.50		1.50	
Satellite antenna diameter, m	4.67		4.67	
Satellite antenna gain, dBi	34.72		34.72	
Satellite antenna beamwidth, deg	3.00		3.00	
EIRP, dBW	48.78		48.78	
Range, km	40,000.00		40,000.00	
Free space loss, dB	188.00		188.00	
Receiver antenna gain, dB	8.00	0.50	5.00	0.50
Received signal power, dBW	–131.22	0.50	–134.23	0.50
Receiver system temperature, dBK	24.10	1.00	24.10	1.00
Receiver G/T, dB/K	–16.10	1.12	–19.10	1.12
N_o, dBW/Hz	–204.50	1.00	–204.50	1.00
C/N_o, dBHz	73.28	1.12	70.27	1.12
E_b/N_o available, dB	19.20	1.12	16.19	1.12
E_b/N_o at beam edge, dB	16.20	1.12	13.19	1.12
E_b/N_o, Gaussian channel, dB	3.30		3.30	
Degradation, mobile channel, dB	0.00		2.00	0.50
Receiver implementation loss, dB	1.50	0.50	1.50	0.50
Interference, dB	0.50	0.50	0.50	0.50
Link margin	10.90	1.32	5.89	1.41

Coherent demodulation, R = 1/2, convolutional code, soft decoding, BER = 1.0E-4, time interleaving diversity

Table 1. DBS–R link budget for portable and mobile reception, transmission frequency of 1.5 GHz, digital audio at 256 kbps (CD quality)

Table 2A. Link parameters as a function of frequency and audio bit rate for broadcasting one DBS–R program over a 3-deg beam

Parameter	Frequency, GHz		
	0.75	1.5	2.4
Satellite antenna diameter, m	9.33	4.67	2.92
Satellite antenna gain, dBi	34.71	34.72	34.72
Coverage beamwidth, deg	3.00	3.00	3.00
Average useful coverage area, M sq km	2.50	2.50	2.50
Average useful coverage area, M sq mi	1.00	1.00	1.00
RF power per 256-kbps (CD-quality) program/beam, W	6.00	25.50	81.00
EIRP per 256-kbps (CD-quality) program/beam, dBW	42.49	48.78	53.81
Bandwidth per CD-quality channel, kHz	300.00	300.00	300.00
RF power per 48-kbps (FM-quality) program/beam, W	1.13	4.78	15.19
EIRP per 48-kbps (FM-quality) program/beam, dBW	35.22	41.51	46.54
Bandwidth per FM-quality channel, kHz	60.00	60.00	60.00
Portable receiver G/T, dB/K	–20.30	–15.92	–11.74
Available link margin for portable reception, dB	6.44	10.89	16.02
Link margin objective for reception in most houses, dB	5.75	8.76	10.80
Mobile receiver G/T, dB/K	–20.30	–19.10	–19.00
Available link margin for mobile reception, dB	4.38	5.88	6.90
Link margin objective for moderate shadowing, dB	4.38	5.88	6.90

Table 2B. Link parameters as a function of frequency and audio bit rate for broadcasting one DBS–R program over a 1-deg beam

Parameter	Frequency, GHz		
	0.75	1.5	2.4
Satellite antenna diameter, m	28.00	14.00	8.75
Satellite antenna gain, dBi	44.25	44.25	44.25
Coverage beamwidth, deg	1.00	1.00	1.00
Average useful coverage area, M sq km	0.28	0.28	0.28
Average useful coverage area, M sq mi	0.11	0.11	0.11
RF power per 256-kbps (CD-quality) program/beam, W	0.67	2.84	9.02
EIRP per 256-kbps (CD-quality) program/beam, dBW	42.49	48.78	53.81
Bandwidth per CD-quality channel, kHz	300.00	300.00	300.00
RF power per 48-kbps (FM-quality) program/beam, W	0.12	0.53	1.69
EIRP per 48-kbps (FM-quality) program/beam, dBW	35.22	41.51	46.54
Bandwidth per FM-quality channel, kHz	60.00	60.00	60.00
Portable receiver G/T, dB/K	–20.30	–15.92	–11.74
Available link margin for portable reception, dB	6.44	10.89	16.02
Link margin objective for reception in most houses, dB	5.75	8.76	10.80
Mobile receiver G/T, dB/K	–20.30	–19.10	–19.00
Available link margin for mobile reception, dB	4.38	5.88	6.90
Link margin objective for moderate shadowing, dB	4.38	5.88	6.90

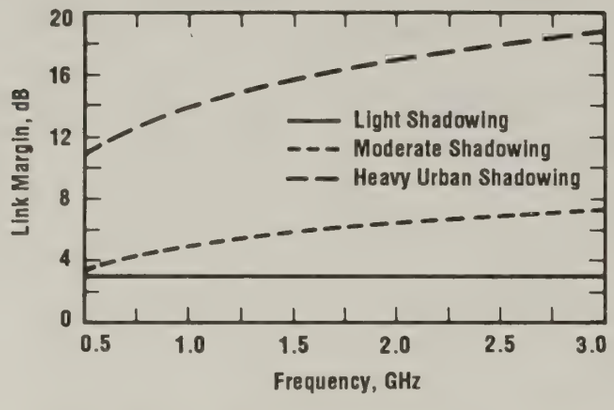

Figure 2. DBS–R link margin, mobile reception.

System Trade-Offs and Cost Estimates for an Example Regional DBS–R Configuration

For our system trade-off and cost estimate study, the DBS–R coverage capacity of a geostationary satellite at 20° E longitude was studied as an example. Such a satellite will have elevation angles of 30 deg or higher over Africa and parts of the Middle East and Southern Europe, as shown in Figure 3. An even larger area is covered within the 10-deg elevation angle contours. Twenty-eight 3-deg beams cover the entire area. The same area can be covered by roughly 252 1-deg spot beams.

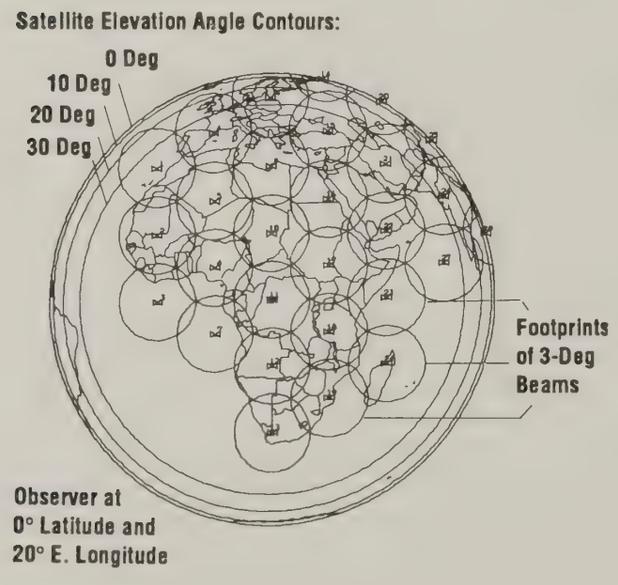

Figure 3. Regional DBS–R coverage for a satellite in geostationary orbit at 20° E longitude.

Figure 4 shows the space segment cost of the example regional DBS–R system as a function of coverage capacity for combinations of the three frequencies (0.75, 1.5 and 2.4 GHz), two beam sizes (3 deg and 1 deg) and two audio qualities (FM-quality digital audio at 48 kbps and CD-quality transmissions at 256 kbps). These cost estimates are based on RF power requirements noted in Tables 2A and 2B using the satellite cost model developed for DBS–R applications. The unit used for coverage capacity is one program broadcast over one million square miles, which is roughly equivalent to one program over a 3-deg spot beam [4]. The satellite RF power requirements are appropriate for mobile reception in rural and suburban areas and portable reception in most houses. Figure 5 shows the per-hour transmission cost estimates for broadcasting one program over one million square miles. These estimates are based on an expected satellite life of 12 years. It is assumed that the satellite capacity will be utilized at an average of 75% of total capacity in recognition of the fact that the broadcasting load varies over the 24 hours in each day. The costs are generally most favorable for the 1.5-GHz implementation. As expected, the per-channel costs are particularly high for low-capacity systems. This trend is observed for all of the configurations shown in Figure 5.

Conclusion

- A single satellite in geostationary orbit has the potential to provide DBS–R services to a vast region of the world for direct reception by low-cost portable, semiportable, mobile and fixed radio receivers.
- The effective isotropic radiated power needed from the satellite for mobile DBS–R reception in suburban areas is sufficient for portable reception in most single family houses when allowance is made for the higher G/T of portable receivers.
- The target G/T figures of merit for DBS–R receivers are approximately

  –20 dB/K for portable reception at 0.75 GHz (5-dBi antenna)

  –20 dB/K for mobile reception at 0.75 GHz (5-dBi antenna)

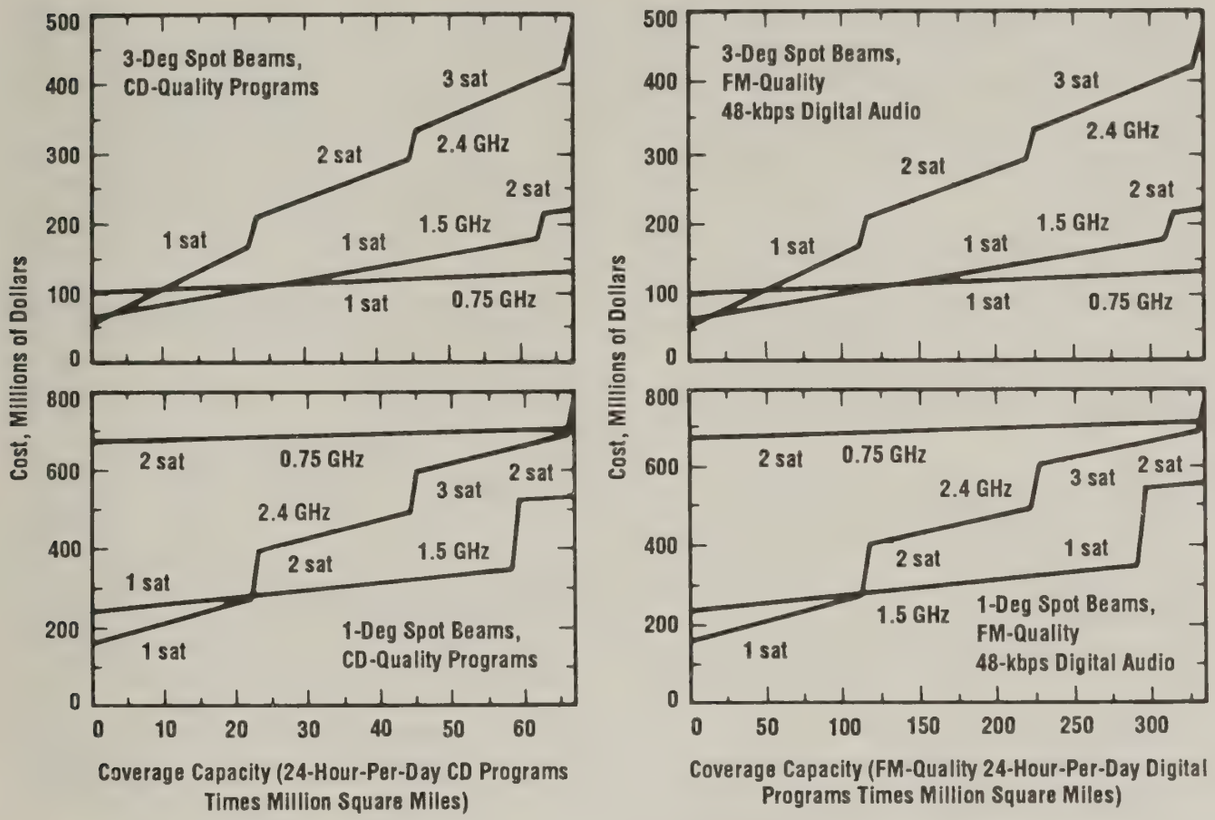

Figure 4. In-orbit DBS–R space segment cost.

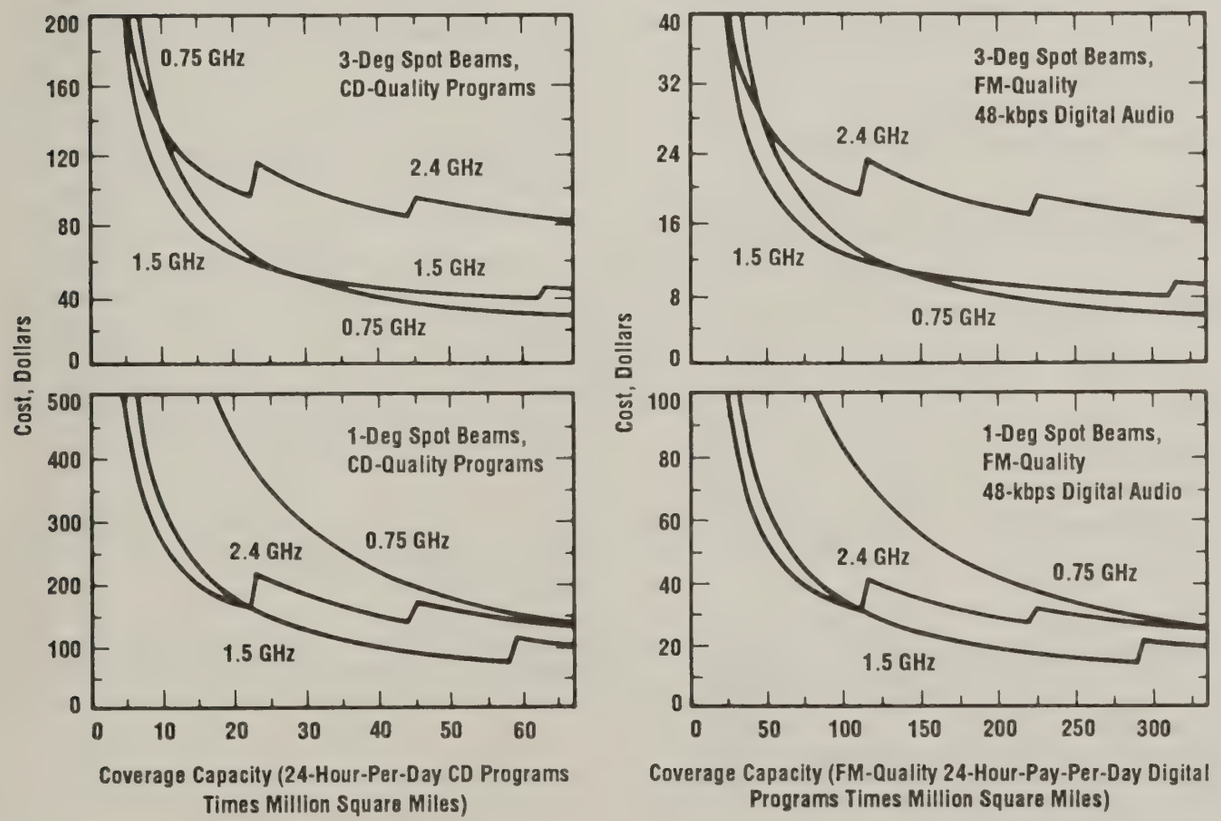

Figure 5. In-orbit regional DBS–R space segment cost per program per hour per million square miles.

–16 dB/K for portable reception at 1.5 GHz (8-dBi antenna)

–19 dB/K for mobile reception at 1.5 GHz (5-dBi antenna)

–12 dB/K for portable reception at 2.4 GHz (12-dBi antenna)

–19 dB/K for mobile reception at 2.4 GHz (5-dBi antenna)

- The per-program RF power requirements for portable reception in most houses and mobile reception in suburban areas are estimated to be as follows:

  For FM-quality digital audio per 3-deg beam:
  1.1 W at 0.75 GHz
  4.8 W at 1.5 GHz
  15.2 W at 2.4 GHz

  For CD-quality digital audio per 3-deg beam:
  6 W at 0.75 GHz
  25.5 W at 1.5 GHz
  81 W at 2.4 GHz

- For a typical regional DBS–R system, implementation at 1.5 GHz would be more favorable than either 0.75 GHz or 2.4 GHz. At 0.75 GHz, the satellite tends to become weight limited due to the large size of the antenna and feed elements, while at 2.4 GHz it will be power limited.

- For a coverage capacity of 20 (CD programs times million square miles) in a 28 3-deg spot beam configuration using a transmission frequency of 1.5 GHz, the in-orbit space segment cost is estimated to be around $100 million, which translates into DBS–R broadcasting costs of $63.50 per CD-quality program per million square miles per hour. For FM-quality digital audio broadcasting at 48 kbps, the corresponding hourly costs are $13 per FM-quality program per million square miles.

- For a coverage capacity of 50 (CD programs times million square miles) in a 28 3-deg spot beam configuration, the in-orbit space segment cost is estimated to be $156 million, which translates into DBS–R broadcasting costs of $39.60 per CD-quality program per million square miles per hour. For FM-quality digital audio broadcasting at 48 kbps, the corresponding hourly costs are $8 per FM-quality program per million square miles.

References

[1] G. Waters and F. Kosamernik, "Plans and Studies in the EBU for Satellite Broadcasting of Sound Radio," *Proceedings of the 13th AIAA International Communication Satellite Systems Conference*, Los Angeles, CA, March 1990, pp. 176–185.

[2] J. E. Miller, "Application of Coding and Diversity to UHF Satellite Sound Broadcasting Systems," *IEEE Transactions on Broadcasting*, Vol. 34, No. 4, December 1988, pp. 465–475.

[3] T. Rogers, "Some Important Advances in International Direct Audio Broadcasting," *Proceedings of the 13th AIAA International Communication Satellite Systems Conference*, Los Angeles, CA, March 1990, pp. 205–208.

[4] N. Golshan, *Direct Broadcast Satellite–Radio Systems Tradeoffs Study, Interim Report*, JPL Internal Document D-8615, June 1991.

[5] D. K. Banks and D. Robson, "The Use of Orthogonal FDM for Sound Broadcasting by Satellites in Highly Inclined Orbits to Overcome Multipath Fading," paper presented at the 13th AIAA International Communication Satellite Systems Conference, Los Angeles, CA, March 1990.

[6] J. D. Johnston, "Transform Coding of Audio Signals Using Perceptual Noise Criteria," *IEEE Journal on Selected Areas in Communications*, Vol. 6, No. 2, pp. 314–323, February 1988.

[7] N. S. Jayant, "High Quality Coding of Telephone Speech and Wideband Audio," to appear in the *IEEE Journal on Selected Areas in Communications*.

[8] E. F. Schroeder, H. J. Platte and D. Krahe, "MSC Stereo Audio Coding With CD-Quality and 256 kBit/Sec," *IEEE Transactions on Consumer Electronics*, Vol. CE-33, No. 4, November 1987, pp. 512–519.

[9] G. Theile, G. Stoll and M. Link, "Low Bit-Rate Coding of High-Quality Audio Signals, an Introduction to the MASCAM System," *EBU Review-Technical*, 230, August 1988, pp. 71–94.

[10] J. Vogel and G. W. Torrence, *Signal Variability Measurements for Satellite Radio Broadcasting Into Buildings*, Technical Report No. 9101, Electrical Engineering Research Laboratory, The University of Texas at Austin, January 1991.

[11] Paul I. Wells, "The Attenuation of UHF Radio Signals by Houses," *IEEE Transactions on Vehicular Technology*, Vol. VT-26, November 1977, pp. 358–362.

[12] G. C. Hess, "Land Mobile Satellite Excess Path Loss Measurements," *IEEE Transactions on Vehicular Technology*, Vol. VT-29, No. 2, May 1980, pp. 290–297.

[13] J. Goldhirsh and W. J. Vogel, "Mobile Satellite System Fade Statistics for Shadowing and Multipath From Roadside Trees at UHF and L-Band," *IEEE Transactions on Antennas and Propagation*, Vol. 37, No. 4, April 1989, pp. 489–498.

[14] W. Vogel and J. Goldhirsch, "Propagation Limits for Land Mobile Satellite Service," *Proceedings of the 13th AIAA International Communication Satellite Systems Conference*, Los Angeles, CA, March 1990, pp. 564–574.

[15] W. J. Vogel and J. Goldhirsh, "Fade Measurements at L-Band and UHF in Mountainous Terrain for Land Mobile Satellite Systems," *IEEE Transactions on Antennas and Propagation*, Vol. 36, No. 1, January 1988, pp. 104–113.

[16] J. Goldhirsh and W. J. Vogel, "Roadside Tree Attenuation Measurements at UHF for Land Mobile Satellite Systems," *IEEE Transactions on Antennas and Propagation*, Vol. AP-35, No. 5, May 1987, pp. 589–596.

[17] W. J. Vogel, et al., "The Australian Experiment With ETS-V," *Proceedings of NAPEX XIII*, June 1989.

[18] W. L. Stutzman, "Mobile Satellite Propagation Measurements and Modeling: A Review of Results for Systems Engineers," *Proceedings of the Mobile Satellite Conference*, May 1988, pp. 107–117.

[19] R. M. Barts and W. L. Stutzman, "Propagation Modeling for Land Mobile Satellite Systems," *Proceedings of the Mobile Satellite Conference*, May 1988, pp. 95–100.

[20] D. C. Nicholas, "Land Mobile Satellite Propagation Results," *Proceedings of the Mobile Satellite Conference*, May 1988, pp. 125–131.

[21] R. J. C. Bultitude, "Measured Characteristics of 800/900 MHz Fading Radio Channels With High Angle Propagation Through Moderately Dense Foliage," *IEEE Journal on Selected Areas in Communications*, February 1987.

[22] K. Dessouky and Loretta Ho, "Field Measurements in MSAT-X," *Proceedings of NAPEX XIII*, June 1989, pp. 18–21.

[23] A. Bundrock and R. Harvey, "Propagation Measurements for an Australian Land Mobile Satellite System," *Proceedings of the Mobile Satellite Conference*, May 1988, pp. 119–124.

[24] J. Van Rees, "Measurement of the Wide-Band Radio Channel Characteristics for Rural, Residential and Suburban Areas," *IEEE Transactions on Vehicular Technology*, Vol. 36, No. 1, February 1987.

[25] J. Goldhirsh and W. Vogel, "Results of 1987 Helicopter Propagation Experiments at UHF and L-Band in Central Maryland," *Proceedings of NAPEX XII*, June 1988, JPL Publication 88-22, pp. 18–26.

Challenges of a General Satellite Service System

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In conjunction with U.S. industry, NASA has proposed obtaining spectrum allocation in the 20/30-GHz bands at the upcoming World Administrative Radio Conference (WARC) in order to enable a new satellite service, the General Satellite Service (GSS). The purpose of this new service is to enable satellite operators flexibility in providing various services dictated by market demand and technological capability.

This article presents a system design to illustrate the technical feasibility of a 20/30-GHz GSS system serving mobile, micro, personal and fixed terminals. In addition, it addresses the frequency separation issue associated with the 20/30-GHz bands. The system design is drawn from Personal Access Satellite System (PASS) research being conducted at JPL [1–4]. PASS, which focuses on personal communications, would be an integral part of a 20/30-GHz GSS system. Figure 1 illustrates the PASS concept.

Applications and Markets

The versatility of small terminals, coupled with the large bandwidth available in the 20/30-GHz bands, permits a diversity of services. In addition to being able to accommodate services offered by mobile satellite systems operating at 1.5/1.6 GHz, GSS can support microterminal- and personal terminal-oriented services that are otherwise not available from current systems. Some of the major services enabled or enhanced by a 20/30-GHz GSS system include

- Direct personal voice and data communications
- Personal computer file transfer
- Database inquiry
- Low-rate voice, data and video broadcasting at the national and regional levels
- Direct data distribution
- Telemonitoring and control
- Disaster and emergency communications

System Architecture

The 20/30-GHz GSS system contains a space segment, a network management center, supplier stations and a number of user terminals. Services are facilitated by properly linking the users and the appropriate service provider. To achieve operational simplicity, the sample system design utilizes fixed multibeams to provide simultaneous, continuous coverage to users in the service area, i.e., the contiguous United States (or CONUS). In addition to the spot beams, a single CONUS beam is employed to complete the user-to-supplier and/or supplier-to-user links. Table 1 lists the salient features of the design.

Satellite and User Terminal Designs

As previously mentioned, the satellite employs both a CONUS coverage antenna and spot-beam antennas. One CONUS antenna will be used for the downlink and uplink signals to and from the supplier stations, network management center and the tracking, telemetry and control (TT&C) station. The spot-beam antennas will be used for users' uplink and downlink. Two multiple spot-beam antennas have diameters of 2 m and 3 m — for transmit and receive, respectively. These antennas produce 142 spot beams covering the service area. The spot-beam antennas have a gain of approximately 52.5 dBi and a 3-dB beamwidth of 0.35 deg. The corresponding receive G/T is 23.4 dB/K and the effective isotropic radiated power (EIRP) is 55 dBW. The CONUS beam receiver G/T is –1.2 dB/K and

the transmitter's EIRP is 40 dBW. Table 2 summarizes the key features of the satellite.

There are five types of user terminals: vehicular mobile terminals (VMTs), aeronautical mobile terminals (AMTs), basic personal terminals (BPTs), microterminals/enhanced personal terminals (EPTs) and telemonitors. The VMTs are similar to mobile terminals in the 1.5/1.6-GHz bands, which consist of a tracking antenna, transceiver, modem, vocoder, handset and other user-interface equipment. The mobile terminal is capable of supporting two-way voice and data communications as well as low-rate broadcasting. The antenna gain ranges from 20 to 25 dBi.

The AMTs are similar to the VMTs with the exception that more than one airborne antenna may be needed to provide the needed coverage.

The BPTs, which represent the major technological challenge, will be equipped with a tracking antenna and will be capable of supporting voice and data services at a rate not exceeding 4.8 kbps under normal operating conditions (i.e., no rain). This type of terminal is required to have an antenna gain of 23 dBi at the transmit frequency and 19 dBi at the receive frequency, a variable rate modem, a 1-W transmitter and other application-dependent components. The variable-rate modem is necessary to compensate for rain attenuation. The BPTs are intended for mobile applications — that is, to be carried around by the user. Table 3 provides the key design requirements of the BPTs; a phased-array antenna has been assumed for its compactness, although other concepts are also applicable (see Figure 2).

The EPTs (or microterminals) are similar to the current VSAT terminals, except for the smaller antenna and the two-way, high-rate capability. With an antenna of 1 ft or less in diameter, the EPTs can have many applications by providing high-quality voice, high-reliability data communications for direct computer file transfer and low-rate video. These terminals are not intended to be mobile. As such, they do not have to be very compact; many antenna concepts are thus applicable [2]. A dish-type antenna with a gain of 32.5 dB at 20 GHz and 36.0 dB at 30 GHz is assumed here. Table 4 summarizes the design requirements for this type of terminal.

The telemonitors are used for remote monitoring and data collection.

Table 1. Sample system design: salient features

Parameter	Feature
Operating frequency	
Uplink, GHz	30
Downlink, GHz	20
Coverage concept	
Sat/suppliers	CONUS beam
Sat/users	142 spot beams
Generic services	Voice and data
Typical channel data rate, kbps	4.8
Rain compensation	
Forward	Uplink power control and variable data rate
Return — BPT type	Variable data rate
Return — EPT type	Uplink power control and variable data rate
Link availability	
BPT type, %	98
EPT type, %	> 98
Interbeam power management	9-beam
Frequency reuse capability	16 times (spot beams)
System capacity	7,500 duplex voice channels equivalent (VOX = 35%)

Frequency Plan

The uplink frequency is 30 GHz and the downlink frequency is 20 GHz. The available uplink and downlink spectra are each divided into two parts for the CONUS beams (feeder links) and the spot beams. To increase spectrum utilization, the spectrum assigned for the spot beams is reused 16 times. There is no reuse for the CONUS beam.

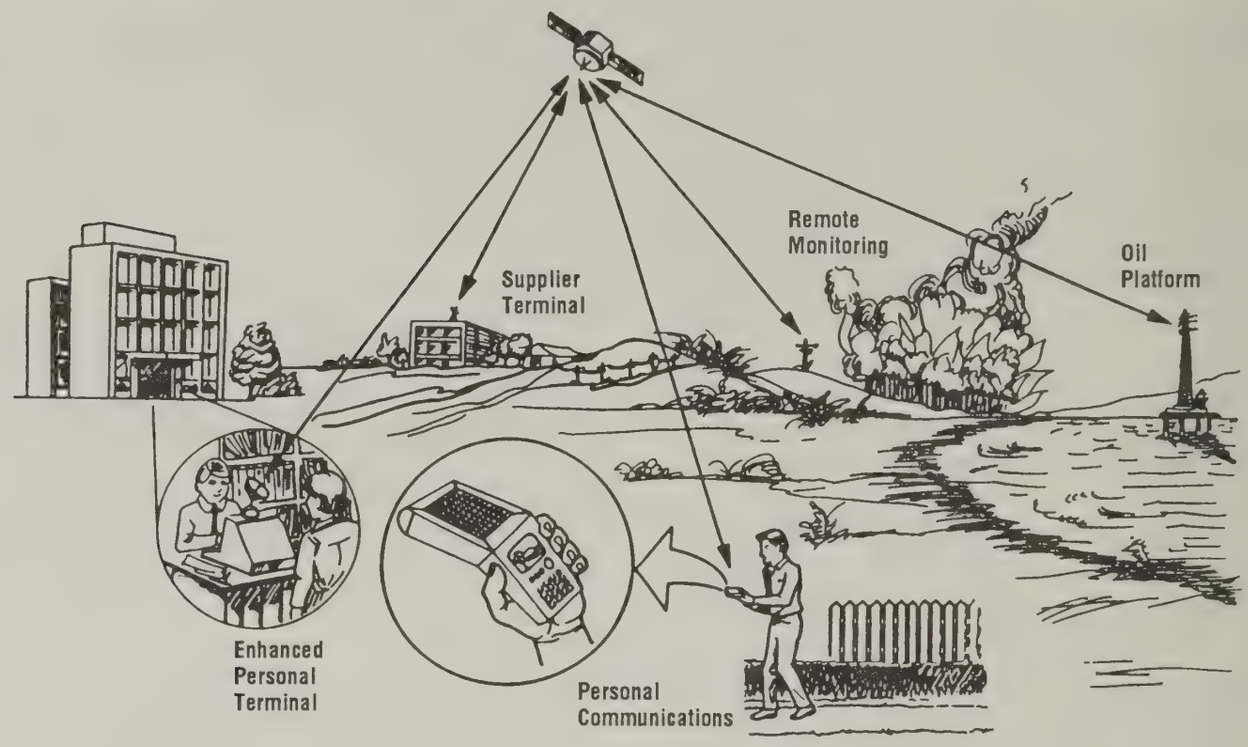

Figure 1. Personal access satellite system concept.

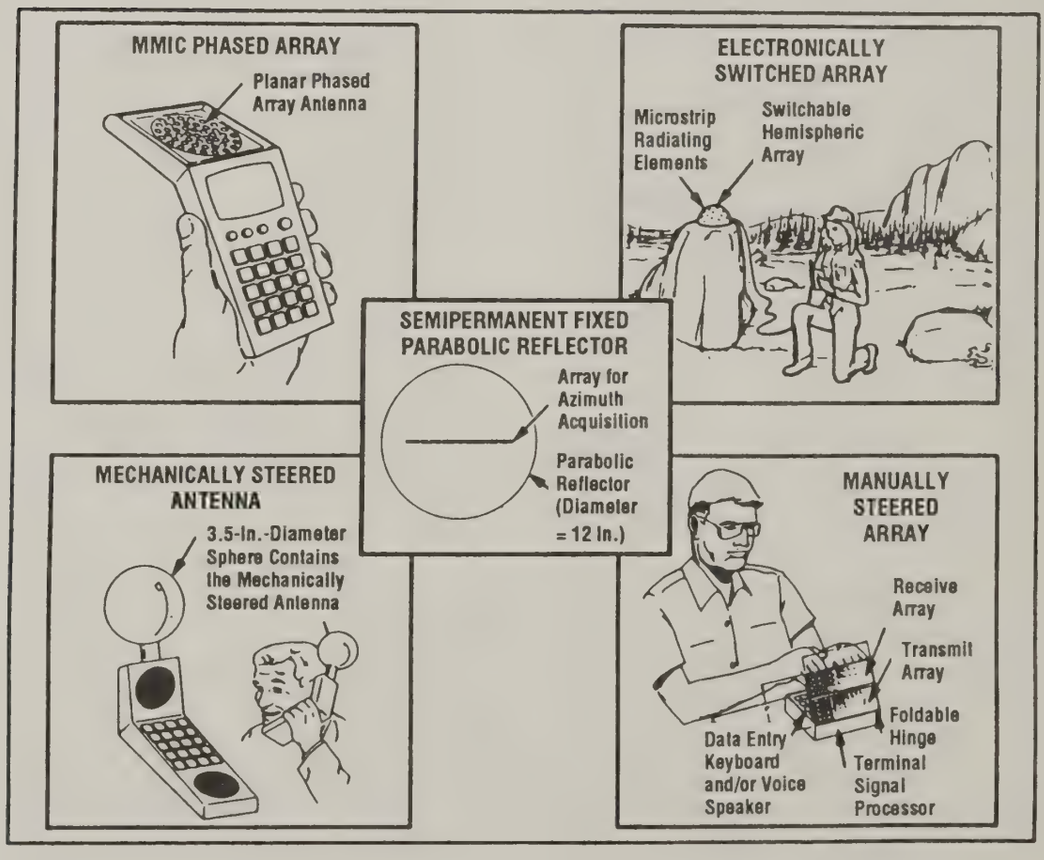

Figure 2. User terminal antenna concepts.

Technological Challenges of the 20/30-GHz Frequency Separation in User Antenna Design

In general, two different types of user antennas can be considered: reflectors and arrays. The reflector antenna, due to its nonconformality and the fact that it would require strictly mechanical steering, is less desirable from an operational point of view. However, in general, it has certain attractive features: it is broadband (in terms of frequency), it has relatively low-feed network loss and it is generally less costly to manufacture. Its bandwidth, of course, is determined by the feed. The feed, which can be either an open waveguide aperture, a horn or a small array of such elements, does not present any major problem in providing the necessary bandwidth.

The planar array of a number of radiating elements may be a more suitable antenna candidate. Although the array can also be steered mechanically in both elevation and azimuth, it is more likely it will be electronically steered in both azimuth and elevation, or at least in elevation with mechanical steering in azimuth, in order to maintain conformality.

The question arises as to whether the use of the uplink (transmit) and downlink (receive) frequencies at around 30 and 20 GHz, respectively, may cause a problem in the design of the user antenna. We illustrate the problem with respect to a planar-array antenna (with electronic steering in both azimuth and elevation, or just mechanical steering in azimuth).

No design problem exists if separate antennas are used for the two modes of operation. Employing two antennas, however, in addition to an increase in the total weight and size, could make the design much more expensive. A single antenna covering both frequencies is preferable. In this case, the transmit and receive antennas will use all or part of the same aperture.

In either case, two approaches are possible. In one approach, broadband array elements can be used to provide operation across the total bandwidth from 20 to 30 GHz. This kind of frequency coverage is not really required, since only a very small frequency band around each of the two uplink and downlink center frequencies is utilized in the system. Furthermore, such a broad bandwidth is difficult to achieve when using relatively simple planar elements.

Table 2. Key satellite feature design summary

Parameter	Feature
Spot beam	
Antenna size, m (transmit)	3.0
Antenna size, m (receive)	2.0
Spot beams, no.	142
Antenna gain, dBi	52.5
Antenna beamwidth, deg	0.35
System G/T, dB/K	23.4
Average EIRP/beam, dBW	58.7
CONUS beam	
Antenna gain, dB	27.0
Antenna beamwidth, deg	7.7
System G/T, dB/K	–1.2
EIRP, dBW	46.1
Satellite mass, lb (GTO)	7,500.0
Satellite power, kW (EOL)	4.0

However, this approach would be relatively simple to implement, if the receive and transmit operating frequencies are very close to each other, with only a few percent total bandwidth (e.g., 20/21.5 or 30/32 GHz). A 40/44-GHz system, with a bandwidth of less than 10%, would also fall in this category. Namely, the same elements can be used to cover both frequency bands.

A better approach is to use collocated elements, such as dual stacked microstrip patches or other dual resonant radiating elements, that cover very narrow frequency bands (on the order of 1%) and are centered at each of the two operating frequencies. This approach has the added advantage of providing an inherent isolation of up to 20 dB between the transmit and receive frequencies, thereby reducing the isolation requirements of the diplexers.

Table 3. BPT design requirements

Parameter	Requirement
Antenna gain @ 20 GHz, dBi	19.3
Antenna gain @ 30 GHz, dBi	22.8
Antenna tracking/coverage capability	
Azimuth, deg	360.0
Elevation, deg	15–60
Receive G/T, dB/K	–9.0
Transmit power, W	0.17
Effective data rate, kbps/channel	4.8
Other requirements	
Size	Hand-held
Modem	Variable rate

Table 4. EPT design requirements

Parameter	Requirement
Antenna gain @ 20 GHz, dBi	32.5
Antenna gain @ 30 GHz, dBi	36.0
Antenna tracking requirement	None
Receive G/T, dB/K	4.2
Transmit power	0.02 W/4.8 kbps with power control
Modem	Variable rate

In yet another approach, the receive and transmit arrays can be separate but interleaved to occupy the same aperture. This approach has the advantage of relatively simple element design, since elements in each array need to operate over a relatively small frequency band. Furthermore, a much better isolation than the collocated elements arrangement can be achieved. However, due to the increased spacing required between the elements of either array in at least one direction, electronic scanning in that direction will create high grating lobes, unless substrates with very high dielectric constants are used to reduce the element size and, hence, spacing.

In general, an interleaving arrangement is most suited to a fully mechanically steered array or a hybrid mechanical/electronic scan array with mechanical scanning in the interleave direction.

In either of the last two approaches, a major problem is the difference in interelement separation in terms of wavelength at the two frequencies, which could cause high grating lobes at the higher frequency, particularly for beams steered to low elevation angles. According to the array theory, if the array elements in a regular grid have a large interelement spacing, grating lobes are produced which manifest themselves as large sidelobes which result in a loss of gain as well as an increase in the received noise temperature. This problem becomes even more significant for large scan angles. Specifically, in order to completely prevent the presence of grating lobes, the interelement spacing should be less than or equal to the following:

$$d = 0.5\lambda / [1 + \sin(\theta)], \text{ for uniform rectangular grid} \quad (1)$$

and

$$d = 0.577\lambda / [1 + \sin(\theta)], \text{ for uniform triangular grid} \quad (2)$$

in which θ is the scan angle from zenith (or broadside of the array). The spacing must definitely be less than twice the above values so that the peak of the first grating lobe does not enter the visible space. For a broadside array (zero scan), the above limits reduce to 0.5λ and 0.577λ, respectively, and decrease as the scan angle is increased. The above values are based on the assumption of isotropic element patterns. The natural taper of an actual element will reduce the grating-lobe levels.

A representative case is illustrated in Figure 3, where a linear array of six elements is considered. Two microstrip patches are stacked at each element position for the 20- and 30-GHz operations. This array can be part of a complete planar array. We are, however, concerned with its performance in the plane of beam scanning in elevation.

Figure 4 shows the broadside and scanned patterns of the linear array of six elements with 0.6-cm interelement spacing. This spacing translates into 0.4λ at 20 GHz (the wavelength at

20 GHz is 1.5 cm); the corresponding spacing for the collocated elements at 30 GHz (with a wavelength of 1 cm) is 0.6λ. This is quite acceptable for the broadside array. However, for the beam scanned to 70 deg from zenith (to provide coverage at 20-deg elevation), this is far larger than the 0.258λ limit obtained from Equation (1), and even larger than the absolute limit of twice that value, i.e., 0.516λ.

It may be noted that the higher taper of the narrower element beamwidth at the higher frequency partially compensates for the higher array grating lobe at this frequency. As can be seen in Figure 4, the performance at 20 GHz is satisfactory for both the scanned and nonscanned cases. For the 30-GHz case, however, the grating lobe is even higher than the main lobe and, of course, is not acceptable.

A better result is obtained if the interelement spacing is reduced to 0.5 cm. In this case, the spacing is 0.33λ at 20 GHz and 0.5λ at 30 GHz. This provides a more acceptable performance, as shown

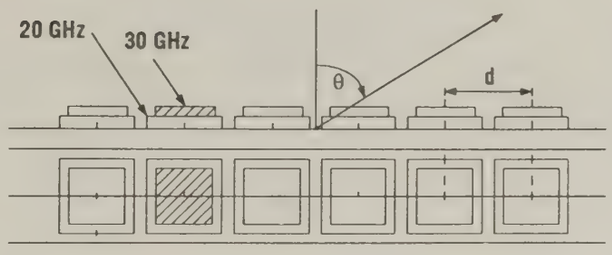

Figure 3. Sketch of a six-element linear array with collocated elements for 20 and 30 GHz and interelement spacing, d.

in Figure 5, although the backlobe for the 30-GHz scanned case is still relatively large. Still smaller separations can yield much lower sidelobes, as shown in Figure 6 (0.4-cm spacing = 0.4λ at 30 GHz = 0.27λ at 20 GHz). In the plots, we have assumed that each element has a half-power beamwidth of 90–105 deg at 30 GHz and 130–145 deg at 20 GHz.

The sidelobes can be further reduced by amplitude tapering of the array elements at the expense of a slight loss in aperture efficiency. Typically, a 5-dB sidelobe reduction can be achieved at a gain loss of about 0.5 dB. Also, as the number of elements are increased, the grating lobe effect is

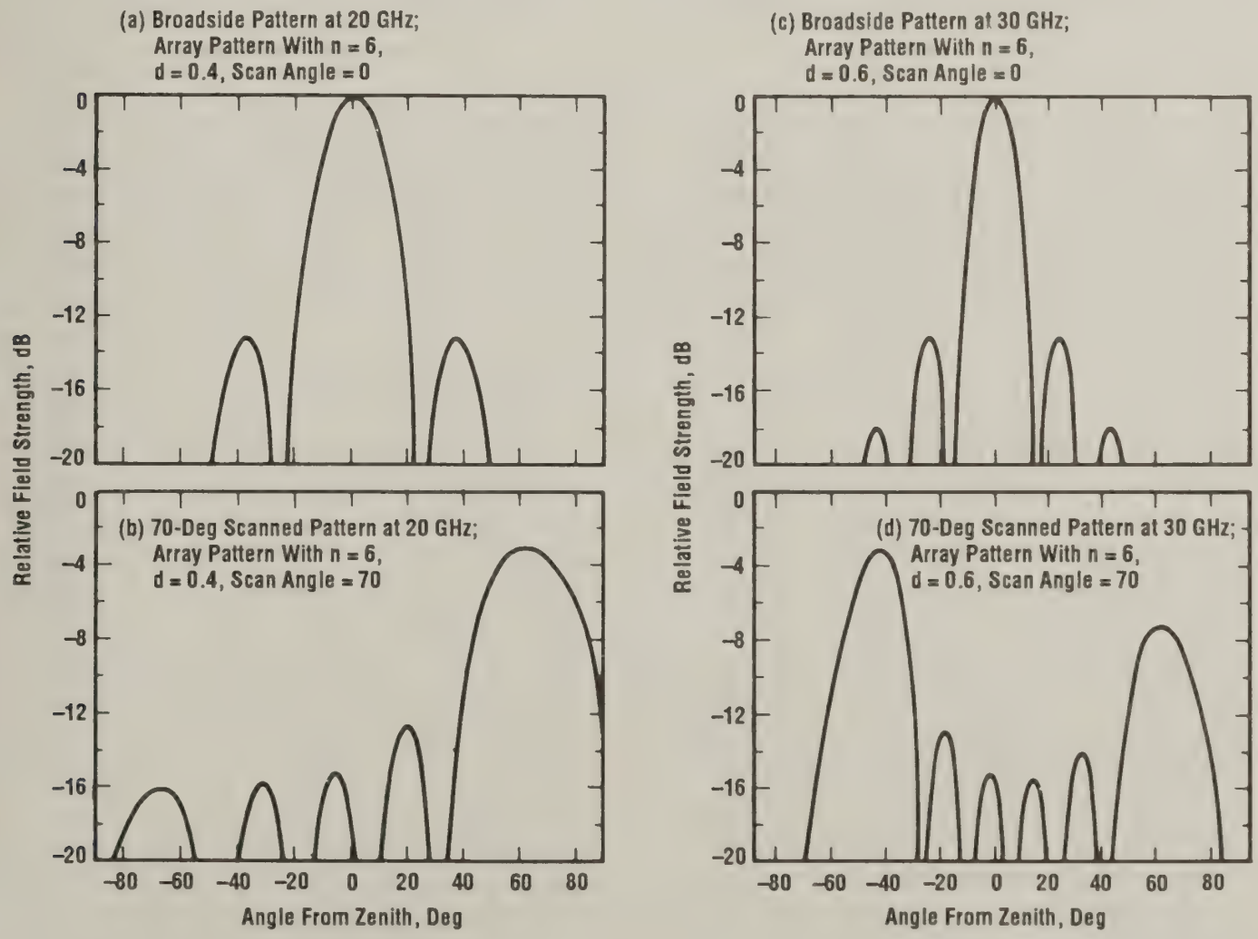
(a) Broadside Pattern at 20 GHz; Array Pattern With n = 6, d = 0.4, Scan Angle = 0
(b) 70-Deg Scanned Pattern at 20 GHz; Array Pattern With n = 6, d = 0.4, Scan Angle = 70
(c) Broadside Pattern at 30 GHz; Array Pattern With n = 6, d = 0.6, Scan Angle = 0
(d) 70-Deg Scanned Pattern at 30 GHz; Array Pattern With n = 6, d = 0.6, Scan Angle = 70
Relative Field Strength, dB
0
-4
-8
-12
-16
-20
-80 -60 -40 -20 0 20 40 60 80
Angle From Zenith, Deg

Figure 4. Patterns of a six-element array at 20 and 30 GHz with 0.6-cm interelement spacing.

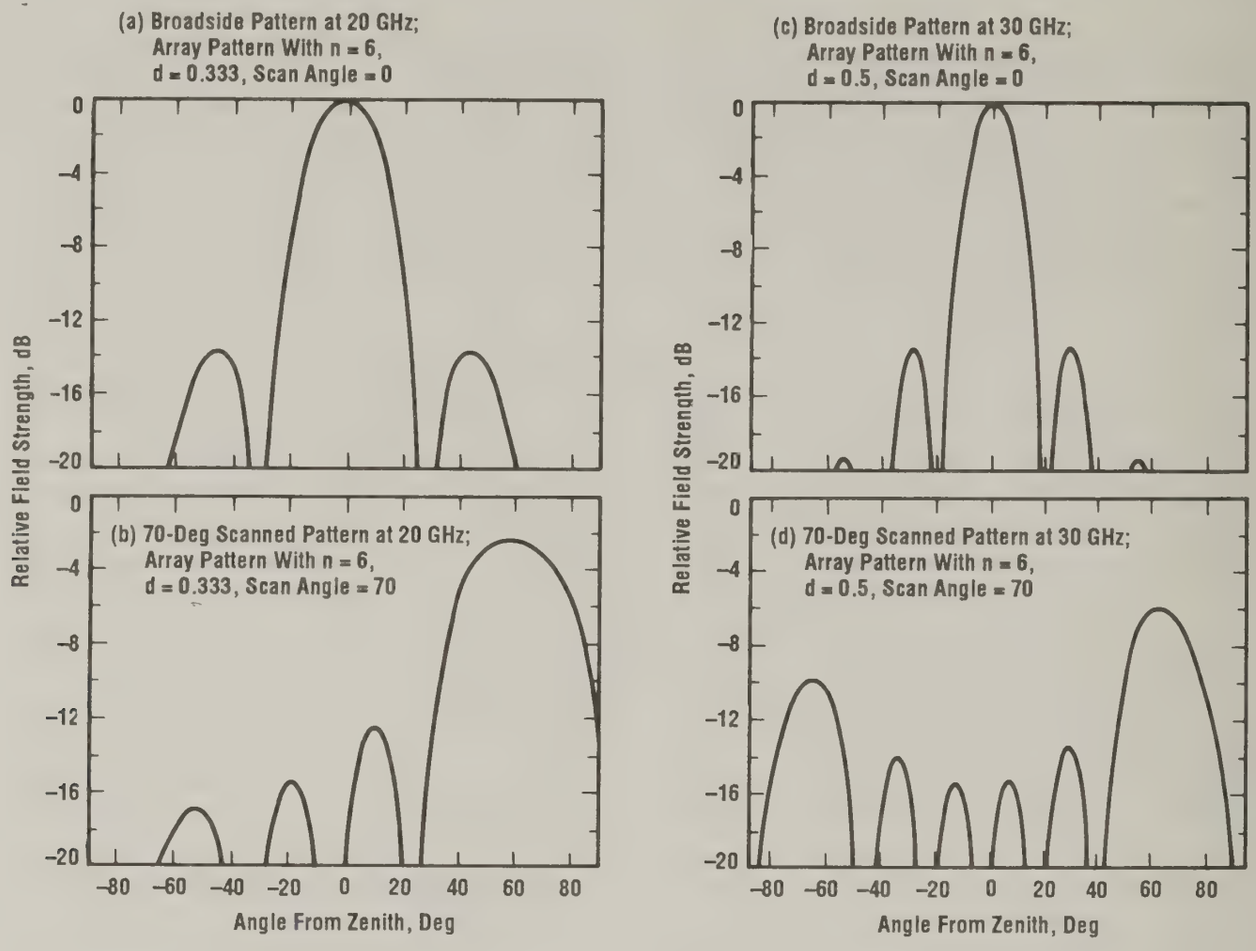
(a) Broadside Pattern at 20 GHz;
Array Pattern With n = 6,
d = 0.333, Scan Angle = 0
(b) 70-Deg Scanned Pattern at 20 GHz;
Array Pattern With n = 6,
d = 0.333, Scan Angle = 70
(c) Broadside Pattern at 30 GHz;
Array Pattern With n = 6,
d = 0.5, Scan Angle = 0
(d) 70-Deg Scanned Pattern at 30 GHz;
Array Pattern With n = 6,
d = 0.5, Scan Angle = 70
Relative Field Strength, dB
0
-4
-8
-12
-16
-20
-80 -60 -40 -20 0 20 40 60 80
Angle From Zenith, Deg

Figure 5. Patterns of a six-element array at 20 and 30 GHz with 0.5-cm interelement separation.

further reduced as long as spacing is less than twice the value given in Equations (1) and (2). Furthermore, by introducing nonuniformity in the array lattice and breaking the symmetry of the configuration, one can reduce or neutralize the grating lobes at the expense of complications in the layout and mechanical design.

It should be noted that a reduction of interelement spacing to accommodate the higher frequency causes the spacing at the lower frequency to be much less than half a wavelength, and since the element size is typically somewhat less than half a wavelength, this may seem to create a problem. This problem, however, can be solved by dielectric loading of the elements (in general, the width of elements is inversely proportional to the square root of the dielectric substrate). Thus, by increasing the dielectric constant, the element aperture can be reduced to fit the available spacing. Typically, however, material with higher dielectric constants have higher losses. Therefore, care must be taken in selecting low-loss dielectrics to avoid efficiency loss.

In any case, as long as the total array aperture is used for operation at both transmit and receive frequencies, the resultant array pattern will be narrower and have a higher gain at the higher frequency (30 GHz). If required, it is possible to employ only an inner subset of the array elements at the higher frequency in order to achieve the same beamwidth and gain as the lower frequency.

Active Versus Passive Arrays

An entirely different but significant issue in the design of the array is the choice of an active versus a passive array. This problem has been analyzed in some detail in [2]. The loss in the so-called beam-forming network (BFN) — the transmission lines, dividers and combiners used to feed the array elements — becomes quite significant, especially at high microwave and millimeter-wave frequencies. In general, this loss in decibels increases proportionally with the log of the number of array elements. The loss associated with the phase shifters used for electronic beam scanning is also quite substantial, particularly for the pin-diode digital phase shifters typically used in microwave monolithic integrated circuit (MMIC) designs.

These losses can substantially reduce — by several decibels — the antenna gain in the transmit

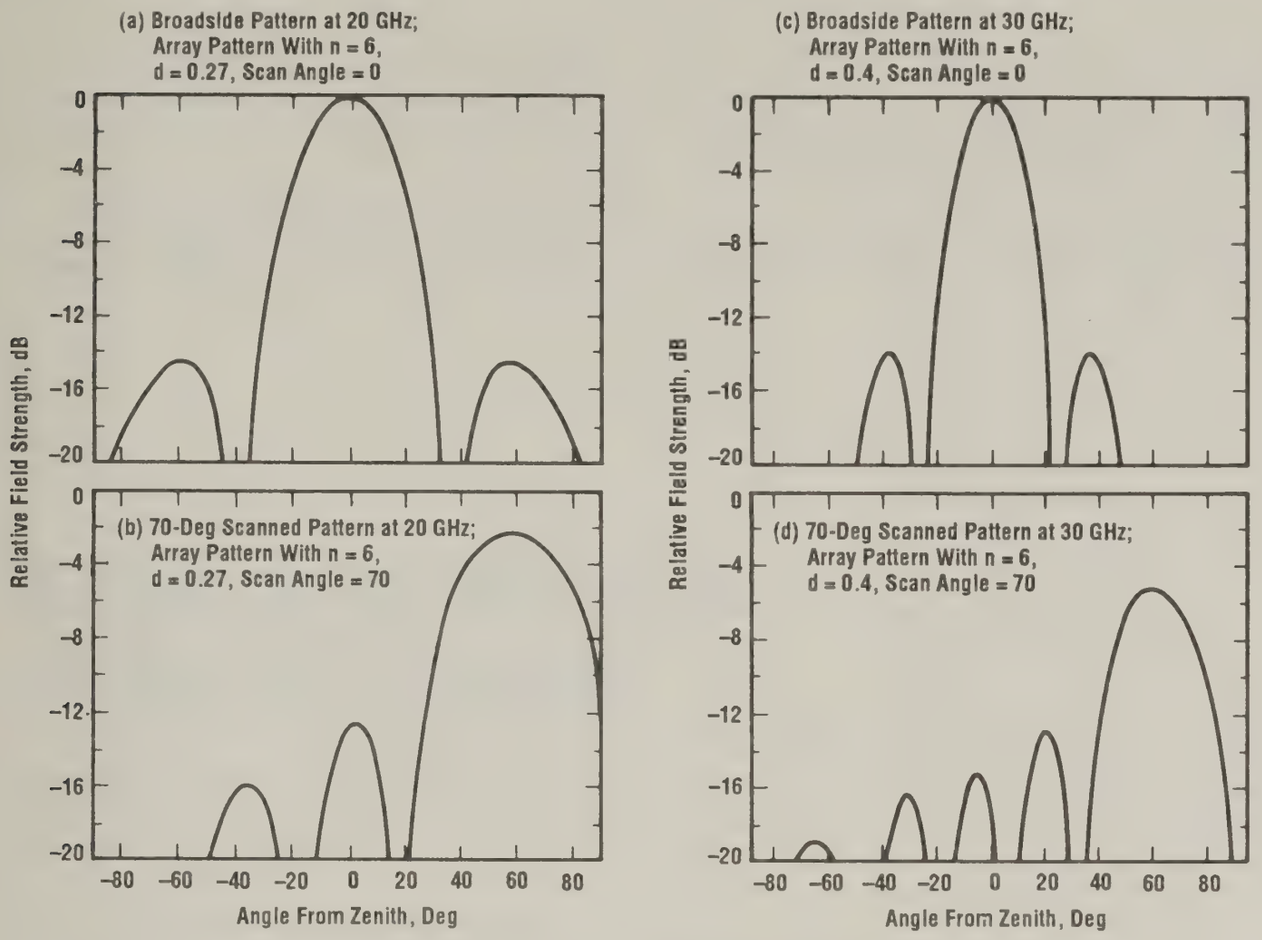
(a) Broadside Pattern at 20 GHz;
Array Pattern With n = 6,
d = 0.27, Scan Angle = 0
(b) 70-Deg Scanned Pattern at 20 GHz;
Array Pattern With n = 6,
d = 0.27, Scan Angle = 70
(c) Broadside Pattern at 30 GHz;
Array Pattern With n = 6,
d = 0.4, Scan Angle = 0
(d) 70-Deg Scanned Pattern at 30 GHz;
Array Pattern With n = 6,
d = 0.4, Scan Angle = 70
Relative Field Strength, dB
0
-4
-8
-12
-16
-20
-80 -60 -40 -20 0 20 40 60 80
Angle From Zenith, Deg

Figure 6. Patterns of a six-element array at 20 and 30 GHz with 0.4-cm interelement separation.

mode and the figure of merit (G/T) in the receive mode. By employing high-power amplifiers (HPAs) for the transmit frequency and low-noise amplifiers (LNAs) for the receive frequency immediately behind individual array elements or a small group (subarray) of elements, the adverse effects of the losses in the beam-forming network can, in effect, be neutralized. The active array approach also increases the transmit-to-receive isolation by reducing the coupling and intermodulation effects via the beam-forming networks, particularly when the BFNs are interleaved or in close proximity. This increase in transmit-to-receive isolation can be explained by the fact that in the active array (at the BFN level), the transmit signal is at the preamplification low-power level, while the receive signal is already amplified. The active array approach is essential at higher microwave/millimeter-wave frequencies of the MMIC design.

The amount of frequency separation, however, does not seem to have any direct bearing on the active versus passive array design, except for the fact that the reduction of the coupling via the BFN in the active array case helps in increasing isolation in the smaller frequency separation case.

User Antenna Selection Summary

In summary, it is quite feasible to obtain reasonable antenna array performance at the 20/30-GHz band by using, for example, dual-stacked microstrip patch elements that provide coverage at both frequencies. This large frequency separation also provides for better isolation between the uplink and downlink paths (simpler diplexers are needed). A simpler antenna design can be employed, however, if the frequency separation is less than 10%, for example the 40/44-GHz range. The latter system will also result in much smaller antenna dimensions for the same gain requirement. This case, however, will require better filtering (diplexing) between the up and down links due to the close proximity of the frequencies. In any case, an active array approach seems to be the preferred and indeed necessary approach for the electronically steered array. Although it is recognized that the wide frequency separation represents a technical challenge to the design of the small user antennas, the analysis presented in this article indicates that it is technically feasible to design a user antenna operating in the 20/30-GHz band with reasonable performance.

References

[1] M. K. Sue, A. Vaisnys and W. Rafferty, "A 20/30-GHz Personal Access Satellite System Study," presented at the 38th IEEE Vehicular Technology Conference, VTC-88, Philadelphia, PA, June 15–17, 1988.

[2] M. K. Sue (editor), *Personal Access Satellite System (PASS) Study, Fiscal Year 1989 Results*, JPL Internal Document D-7382, September 1990.

[3] M. K. Sue, K. Dessouky, B. Levitt and W. Rafferty, "A Satellite-Based Personal Communication System for the 21st Century," International Mobile Satellite Conference, Ottawa, Ontario, Canada, June 18–20, 1990.

[4] B. K. Levitt, W. Rafferty, M. K. Sue and K. Dessouky, "A Satellite-Based Personal Communication System for the 21st Century," *MSAT-X Quarterly*, No. 25, Jet Propulsion Laboratory, October 1990.

A Spectral Analysis of the 20-GHz ACTS Beacon

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Thanks are due Chaim Zaks, P. Levine and F. Davarian for many useful discussions.

The Advanced Communications Technology Satellite (ACTS) will have two noncoherent beacons: one beacon in the uplink frequency (27.5 GHz) band and the other in the downlink frequency (20 GHz) band. These two beacons will be used for signal fade and radiometric measurements. The salient characteristics of these two beacons are shown in Table 1 [1], where most of these characteristics have been verified experimentally [2].

The 20-GHz beacon will be derived from a phase modulator, where the residual carrier power will act as the beacon source. The sideband power will carry telemetry data and ranging information. The telemetry and ranging signal multiplexing process is shown in Figure 1. The two 20-GHz beacons can be transmitted simultaneously or in the vertical polarization (V-Pol) or horizontal polarization (H-Pol) modes; normally the V-Pol mode will be used, but provisions will be made to transmit in both polarizations. The 20-GHz beacon transmitter block diagram is shown in Figure 2 [2]. The input to the phase modulator is composed of multiplexed phase shift keying (PSK) telemetry data and a square-wave ranging signal; the output will contain sidebands as well as beat tones [3]. These beat frequencies will appear close to the beacon.

In a recent simulation study [4], significant spectral products close to the ACTS downlink beacon frequency were observed. These unwanted products may give rise to a false lock scenario in ACTS propagation receivers during the wideband initial search mode or after a prolonged deep fade unless an appropriate software control algorithm is provided for the selection of the maximum signal component in the presence of unwanted adjacent spikes.

The purpose of this article is to analyze and calculate the locations and magnitudes of these unwanted products so that an appropriate software control algorithm can be developed for incorporation with the ACTS propagation receive terminals to avoid false locks.

Unwanted spectral products close to the ACTS downlink beacon frequency have been observed. Their locations and magnitudes must be determined so that measures can be taken to avoid false locks.

There are five cases of multiplexed modulating signals, shown in Table 2, where PSK telemetry (TLM) data are assumed to be present (1,024 bps maximum).

We will first discuss the basic theory of beat frequency generation, manually solve a simple case to demonstrate the presence of these beat frequency spikes and compare the results when using a computer simulation model before simulating the cases described in Table 2.

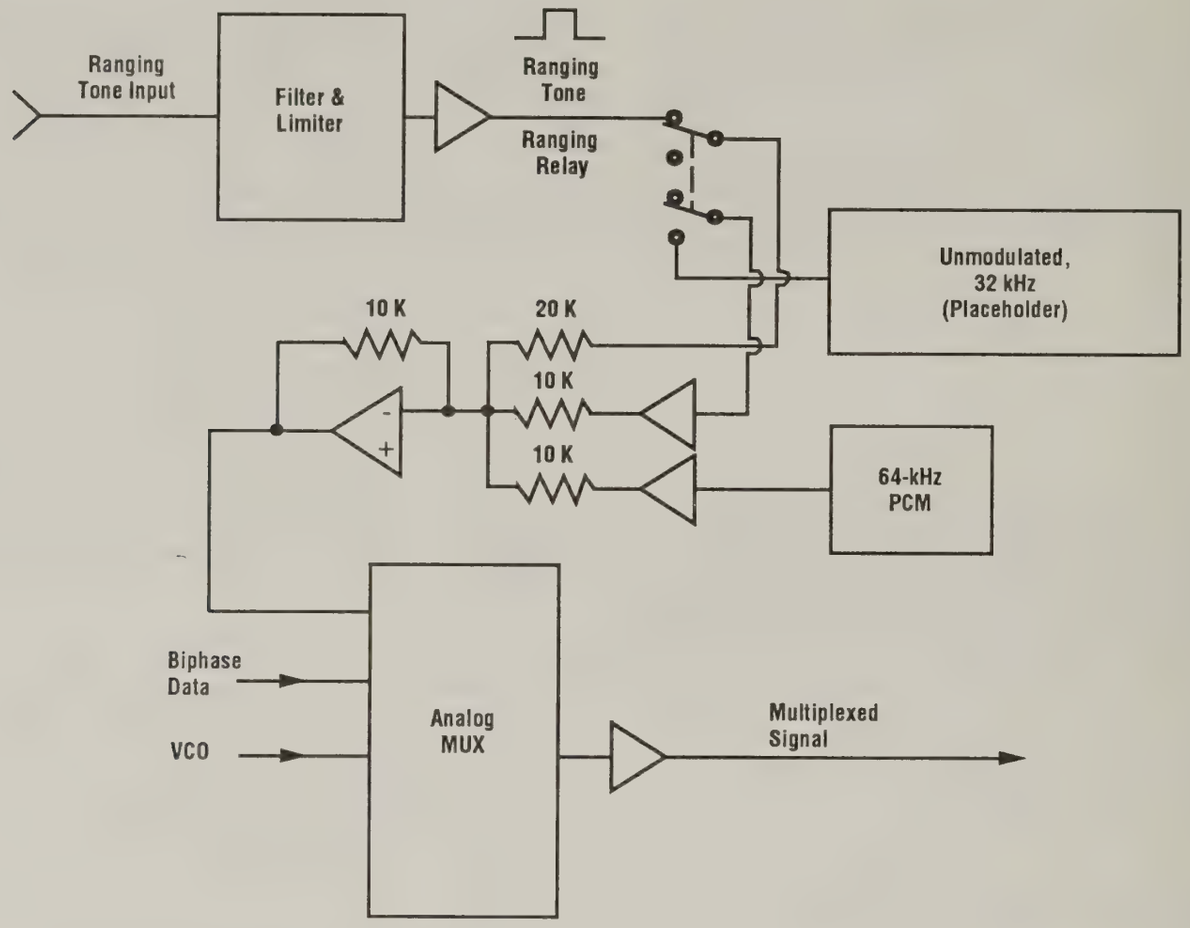


Figure 1. ACTS telemetry subcarrier generation.

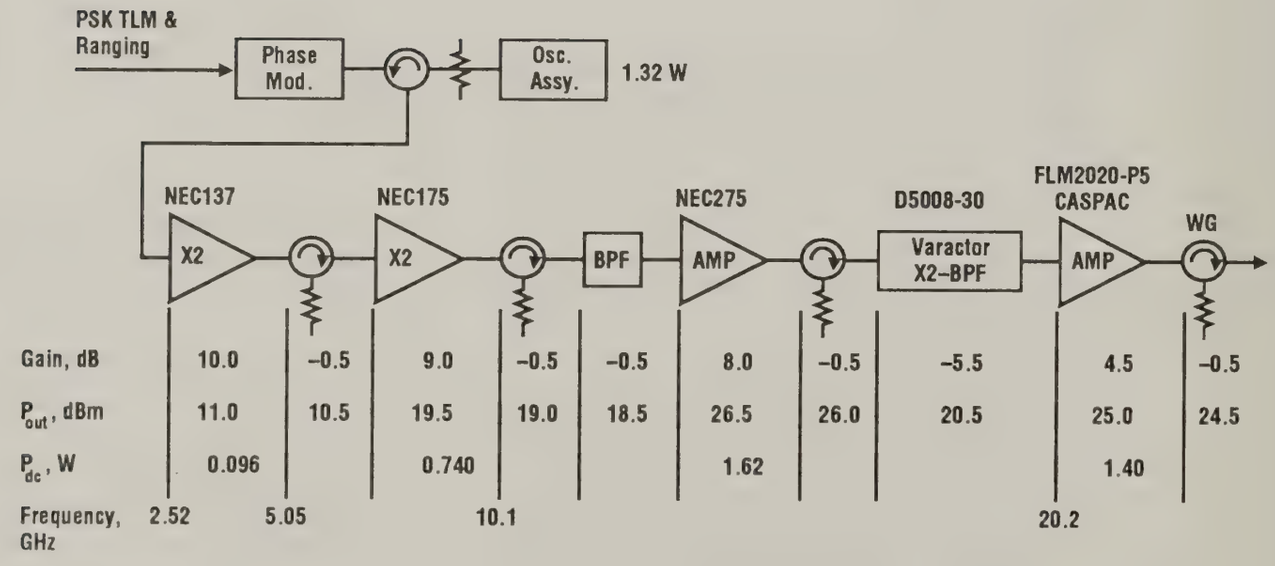


Figure 2. 20.2-GHz Ka-band beacon transmitter.

Table 1. ACTS beacon characteristics

Parameter	27.5-GHz beacon	20-GHz beacon
Beacons, no.	1	2
Frequency/polarization	27.505 GHz ±0.5 MHz (V)	20.185 GHz ±0.5 MHz (V); 20.195 GHz ±0.5 MHz (H)
Function	Fade measurement	Telemetry/fade measurement
Modulation	None	Yes (FM and PCM)
Nominal RF output, dBm	20	23
Operating temperature, °C	–10 to +55	–10 to +55
Frequency stability	±10 PPM over 2 yr at constant temperature; ±1.5 PPM over 24 hr for –10° C to +55° C	
Output power stability	±1.0 dB over 24 hr; ±2.09 dB over full mission	
Phase noise	–49 dBC/Hz at 50 Hz; –80 dBC at 3000 Hz	–51 dBC/Hz at 50 Hz; –92 dBC/Hz at 19 kHz

Table 2. Multiplexed modulating signal configuration

Case	Combination	Frequencies relative to beacon, kHz	Ranging tone modulation
1	PSK TLM/placeholder	64/32	
2	PSK TLM/ranging	64/27.777	Square wave
3a	PSK TLM/ranging	64/19	35.4 Hz (square wave)
3b	PSK TLM/ranging	64/19	283.4 Hz (square wave)
3c	PSK TLM/ranging	64/19	3968.2 Hz (square wave)

Basic Theory

To illustrate the case, let us first consider a carrier being frequency- or phase-modulated by two tones not harmonically related [3]. The instantaneous angular frequency of a modulated carrier can be written as

$$\omega_i(t) = \omega_c + \Delta\omega_1 \cos(\omega_1 t) + \Delta\omega_2 \cos(\omega_2 t) \quad (1)$$

where

$\omega_c = 2\pi f_c$ = carrier angular frequency

$\Delta\omega_1$ = maximum frequency deviation due to first modulating tone

$\omega_1 = 2\pi f_1$ = angular frequency of first modulating signal

$\Delta\omega_2$ = maximum frequency deviation due to second modulating tone

$\omega_2 = 2\pi f_2$ = angular frequency of the second modulating tone

$\beta_1 = (\Delta\omega_1/\omega_1)$ = modulation index due to first modulating signal

$\beta_2 = (\Delta\omega_2/\omega_2)$ = modulation index due to second modulating signal

From quasistationary approximation, we know that instantaneous angular frequency

$$\omega_i = \frac{d}{dt}(\text{phase}) \quad \text{or} \quad \text{phase} = \int \omega_i \, dt$$

and hence phase and frequency modulation analysis differs only by a mathematical transformation.

The generalized single-tone-modulated FM signal can be written as

$$e(t) = A_c \sum_{k=-\infty}^{\infty} J_k(\beta) \sin(\omega_c + k\omega_1)t \quad (2)$$

where

A_c = unmodulated carrier amplitude

$J_k(\beta)$ = Bessel function of first kind, order k and argument ß (modulation index)

$k = 0, \pm 1, \pm 2, \pm 3, \ldots$

Therefore,

$$\text{Modulated carrier power} = \left[A_c J_0(\beta)\right]^2$$

$$\text{Carrier power relative to unmodulated carrier power} = \frac{1}{\left[J_0(\beta)\right]^2}$$

Similarly,

$$\text{Relative power due to first sideband} = \frac{1}{\left[J_1(\beta)\right]^2}$$

$$\text{Relative power due to second sideband} = \frac{1}{\left[J_2(\beta)\right]^2}$$

and so on.

The two-tone, nonharmonically related, modulated signal becomes

$$e(t) = A_c \exp j(\omega_c t + \beta_1 \sin \omega_1 t + \beta_2 \sin \omega_2 t) =$$

$$A_c \left[\sum_{n=-\infty}^{\infty} J_n(\beta_1) \exp(jn\omega_1 t)\right] \times \left[\sum_{m=-\infty}^{\infty} J_m(\beta_2) \exp(jm\omega_2 t)\right] \exp(j\omega_c t) \quad (3)$$

In a similar way, it can be shown that when the carrier is modulated by nonharmonically related N-tone, 1, 2, . . ., N, with angular frequencies ω_1, ω_2, . . ., ω_N and modulation indices β_1, β_2, . . ., β_N, the instantaneous angular frequency becomes

$$\omega_i(t) = \omega_c + \Delta\omega_1 \cos \omega_1 t + \Delta\omega_2 \cos \omega_2 t + \ldots + \Delta\omega_N \cos \omega_N t \quad (4)$$

where

$$\beta_1 = (\Delta\omega_1/\omega_1),\ \beta_2 = (\Delta\omega_2/\omega_2),\ \ldots,\ \beta_N = (\Delta\omega_N/\omega_N)$$

The modulated signal becomes

$$e(t) = A_c \left[\sum_{n_1=-\infty}^{\infty} J_{n_1}(\beta_1) \exp(jn_1\omega_1 t)\right] \times \left[\sum_{n_2=-\infty}^{\infty} J_{n_2}(\beta_2) \exp(jn_2\omega_2 t)\right] \ldots$$

$$\times \left[\sum_{n_N=-\infty}^{\infty} J_{n_N}(\beta_N) \exp(jn_N\omega_N t)\right] \exp(\omega_c t) \quad (5)$$

As an illustration, we will use Equation (3) to manually calculate the beacon spectral components as applicable to Case 2 discussed in Table 2, assuming a cw tone containing the PSK telemetry channel power and a ranging cw tone at 27.7 kHz. Table 3 presents the components that are produced at the output of the phase modulator for this special case.

It should be noted that with two-tone modulation, the power of the spectral components is reduced when compared to a single-tone modulation case with the same modulation index. This is due to the fact that the power of each component is determined by the product of two Bessel functions. For example, with a single-tone modulation index of 1·1, $J_o(1{\cdot}1) = 0.7196$, resulting in a modulated carrier power of –2.8 dB relative to the unmodulated carrier. With two-tone modulation, the modulation index should be chosen such that the modulated carrier power (beacon power) is the same as in the case of single-tone modulation. This can be achieved by choosing $ß_1 = ß_2 = 0.79$ and hence $J_o(ß_1) = J_o(ß_2) = 0.85$, resulting in a carrier power (beacon power) –2.8 dB below the unmodulated carrier power, and the first sideband becomes $[J_1(ß_1)\, J_o(ß_2)]^2 = [0.3650 \times 0.8500]^2 = -10.2$ dB, relative to the unmodulated carrier power.

We will now calculate the beacon spectra for a simplified Case 2 with the following assumptions:

- Beacon center frequency reference = 0
- Relative location (f_1) of ranging tone with respect to the beacon = 27.7 kHz
- Relative location (f_2) of PSK telemetry channel center frequency with respect to the beacon = 64 kHz
- Equal modulation indices ($ß_1 = ß_2$) = 0.79
- Analysis bandwidth = ±100 kHz
- PSK subcarrier simulated by a cw tone

The calculated spectral components for the above parameters are shown in Table 4. Table 4 also illustrates the results obtained using the communication system simulator [5] for validating the simulator model.

The last two columns in Table 4 show the comparison of the exact calculations and the computer simulation results of the trial solution under consideration. The Fast Fourier Transform (FFT) process is used in the simulation with finite sampling for the spectral analysis. As a result, FFT points do not always fall on the spectral peaks, and from Table 4 it is also noted that the exact values and the computer simulation results are very close.

Table 3. Spectral components with two-tone

Component	Spectral power	Power relative to unmodulated carrier $[A_c]^2$
Carrier	$[J_o(\beta_1)\, J_o(\beta_2)\, A_c]^2$	$\dfrac{1}{[J_o(\beta_1)\, J_o(\beta_2)]^2}$
Sidebands due to ω_1	$[J_n(\beta_1)\, J_o(\beta_2)\, A_c]^2$	$\dfrac{1}{[J_n(\beta_1)\, J_o(\beta_2)]^2}$
Sidebands due to ω_2	$[J_m(\beta_2)\, J_o(\beta_1)\, A_c]^2$	$\dfrac{1}{[J_m(\beta_2)\, J_o(\beta_1)]^2}$
Beat frequencies at $\omega_c \pm n\omega_1 \pm m\omega_2$	$[J_n(\beta_1)\, J_m(\beta_2)\, A_c]^2$	$\dfrac{1}{[J_n(\beta_1)\, J_m(\beta_2)]^2}$

Table 4. 20-GHz beacon spectral power (trial solution)

Components	Location, kHz	Spectral power relative to $[A_c]^2$, dB		Power relative to beacon, dB	
				Manual calculations	Simulation
Carrier (unmodulated)	0.0	$[A_c]^2$	0.0		
Beacon (modulated)	0.0	$A_c^2[J_0(\beta_1)\ J_0(\beta_2)]^2$	–2.8	0.0	0.0
First S/B due ω_1	±27.7	$A_c^2[J_1(\beta_1)\ J_0(\beta_2)]^2$	–10.2	–7.4	–7.3
Second S/B due ω_1	±55.4	$A_c^2[J_2(\beta_1)\ J_0(\beta_2)]^2$	–24.0	–21.2	–21.2
Third S/B due ω_1	±83.1	$A_c^2[J_3(\beta_1)\ J_0(\beta_2)]^2$	–41.5	–38.7	–38.8
First S/B due ω_2	±64.0	$A_c^2[J_1(\beta_2)\ J_0(\beta_1)]^2$	–10.2	–7.4	–7.6
Beat frequencies $0 \pm n\omega_1 \pm m\omega_2$					
$n = 1, m = 1$; $n = -1, m = -1$	±91.7	$A_c^2[J_1(\beta_1)\ J_1(\beta_2)]^2$	–17.5	–14.7	–15.0
$n = 1, m = -1$; $n = -1, m = 1$	±36.3	$A_c^2[J_1(\beta_1)\ J_{(-1)}(\beta_2)]^2$	–17.5	–14.7	–14.9
$n = 2, m = -1$	–8.6	$A_c^2[J_2(\beta_1)\ J_{(-1)}(\beta_2)]^2$	–31.4	–28.6	–28.0
$n = 2, m = -2$	–72.6	$A_c^2[J_2(\beta_2)\ J_{(-2)}(\beta_2)]^2$	–45.2	–42.4	–42.2
$n = -2, m = -1$	8.6	$A_c^2[J_{(-2)}(\beta_1)\ J_1(\beta_2)]^2$	–31.4	–28.6	–28.9
$n = 3, m = -1$	19.1	$A_c^2[J_3(\beta_1)\ J_{(-1)}(\beta_2)]^2$	–48.9	–46.1	–46.7
$n = 3, m = -2$	–44.9	$A_c^2[J_3(\beta_1)\ J_{(-2)}(\beta_2)]^2$	–62.7	–59.9	–59.7
$n = -3, m = 1$	–19.1	$A_c^2[J_{(-3)}(\beta_1)\ J_1(\beta_2)]^2$	–48.9	46.1	–46.6
$n = -3, m = 2$	44.9	$A_c^2[J_{(-3)}(\beta_1)\ J_2(\beta_2)]^2$	–62.7	–59.9	–59.1

In summary, the simulation method yields satisfactory results. All the cases mentioned in Table 2 will now be examined using the computer simulation via a Signal Processing Worksystem (SPW) [5].

Computer Simulation Method and Results

The spectral analysis for the ACTS signal formats of Table 2 is performed using the SPW. The SPW is used to model a signal synthesizer that generates signals with specified parameters and modulation formats. Without any loss of generality, the simulation and modeling of the signal synthesizer are performed at baseband since this requires a lower sampling frequency compared to the simulation at the beacon center frequency. Figure 3 illustrates the block diagram of the implemented signal synthesizer. It consists of two major blocks for generating a ranging tone and a data component. In Figure 3, the ranging or placeholder tone is generated using two function generators that synthesize the ranging center frequency and the ranging subcarrier frequency. The data component is synthesized using a function generator for the data center frequency and a random data generator for synthesizing the NRZ data. The parameters for the function and data generators are summarized in the parameter table provided in Figure 3. The ranging and data signal components are then combined to yield

$$\beta_1 \, R(t) \sin(\omega_1 t) + \beta_2 \, S_d(t) \sin(\omega_2 t)$$

where

$R(t) \equiv$ ranging signal

$S_d(t) \equiv$ NRZ random data sequence

$\omega_1 \equiv$ ranging signal center frequency

$\omega_2 \equiv$ data component center frequency

$\beta_1 \equiv$ ranging modulation index

$\beta_2 \equiv$ data component modulation index

The combined signal is then followed by the phase modulator, resulting in a complex baseband signal.

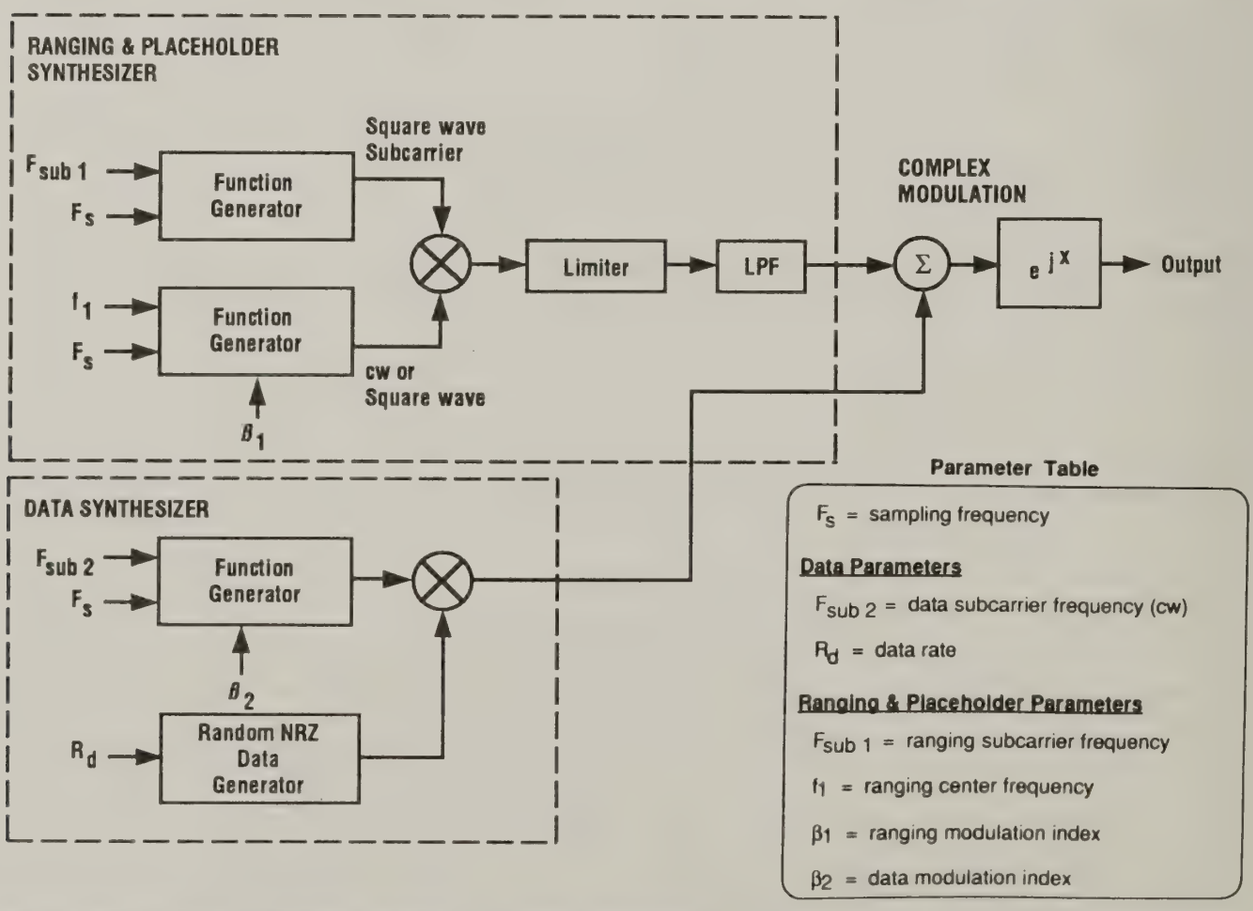


Figure 3. ACTS experiment signal synthesizer at baseband.

Figure 4 illustrates the system's functional block diagram; parameters presented in the figure correspond to Case 2 of Table 2. The implemented models using SPW are digital; therefore, the sampling frequency for the system is selected to meet the Nyquist criterion [6] for the highest frequency component in the analysis bandwidth (100 kHz). Furthermore, the simulation period is chosen so that a minimum of 100 data symbols is simulated.

The synthesizer described above is used for analyzing the spectral properties of the ACTS signal formats at a sampling frequency of 200 kHz with a simulation period of 20,000 points and an FFT length of 32,768 points. The results of the FFT analysis are presented in Figures 5, 6, 7, 8 and 9 for Cases 1, 2, 3a, 3b and 3c, respectively. Each figure also illustrates a summary of the signal parameters and the signal characteristics. Also presented in these figures are the relative frequency and the peak power ratio of the spectral components down to about 20 dB with respect to the beacon power.

The results of the spectral analysis are directly dependent on the modulation index. In this article, a modulation index of 0.79 was used for both the ranging and the data components. The re-

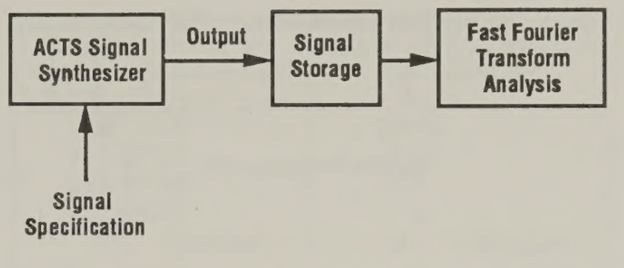


Figure 4. Simulation block diagram.

Parameters for Case 2

Sampling frequency = 200 kHz

f_1 = 27.777 kHz (square wave, no subcarrier)

Data Specification

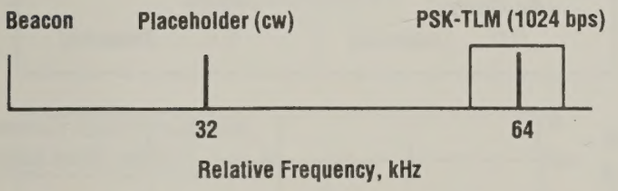
$F_{sub\ 2}$ = 64.0 kHz (subcarrier frequency)

R_d = 1024 bps (data rate)

$\beta_1 = \beta_2 = 0.79$ (modulation index)

Simulation length = 20,000 points

FFT length = 32,768 points



SIGNAL CHARACTERISTICS, CASE 1 OF TABLE 2

f_1 = 32 kHz (cw placeholder)
f_2 = 64 kHz (PSK carrier)
R_d = 1024 bps (PSK data rate)
$\beta_1 = \beta_2 = 0.79$

Relative Frequency With Respect to the Beacon (kHz)	Attenuation With Respect to the Beacon (dB)
32.00073	-7.49
64.00146	-19.9
0.0 (beacon)	0.0 (beacon)
-64.08691	-20.3
-32.00073	-7.38

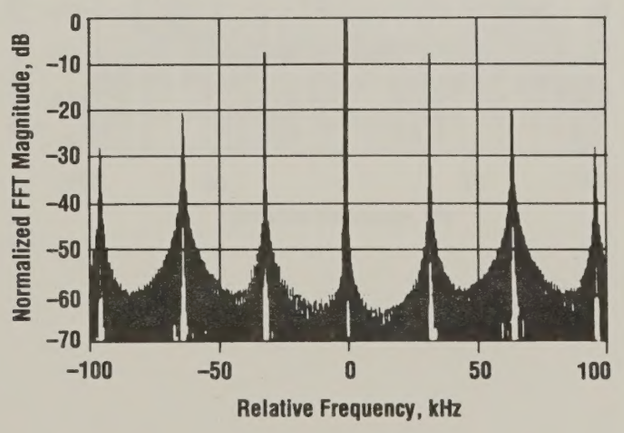
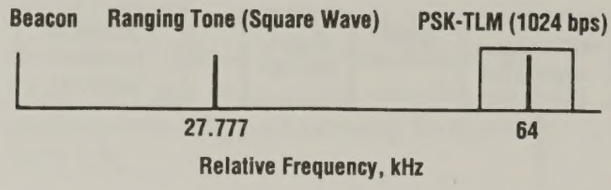


Figure 5. Baseband spectral characteristics of Case 1.

Figure 6. Baseband spectral characteristics of Case 2.



Relative Frequency With Respect to the Beacon (kHz)	Attenuation With Respect to the Beacon (dB)
±27.777	-10.0
±36.13281	-25.0
±64.08691	-15.7
±91.86401	-24.7
0.0 (beacon)	0.0 (beacon)

SIGNAL CHARACTERISTICS, CASE 2 OF TABLE 2

f_1 = 27.777 kHz (square wave)
f_2 = 64 kHz (PSK carrier)
R_d = 1024 bps (PSK data rate)
$\beta_1 = \beta_2 = 0.79$

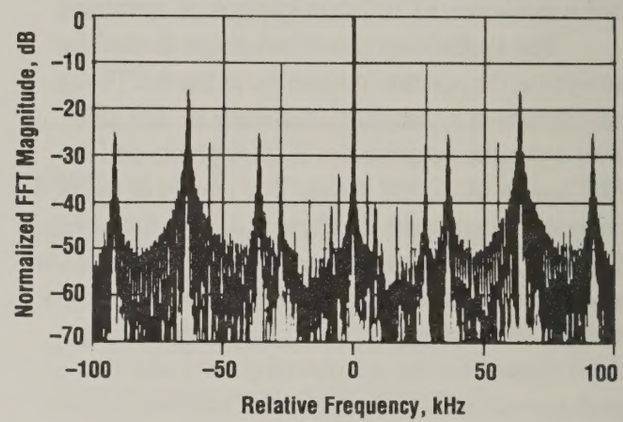
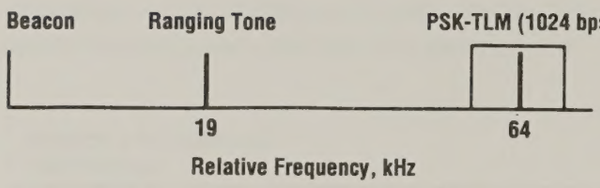


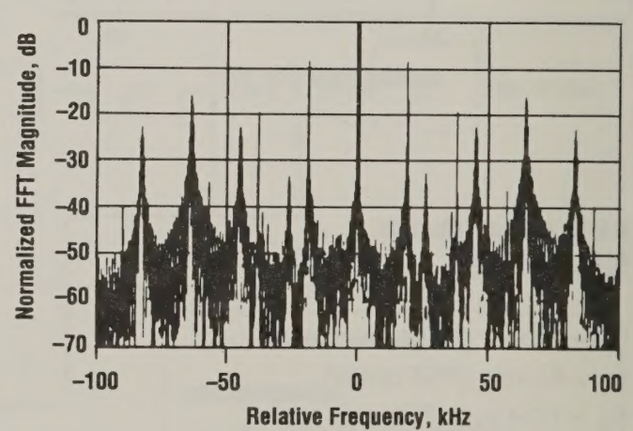
Figure 7. Baseband spectral characteristics of Case 3a.

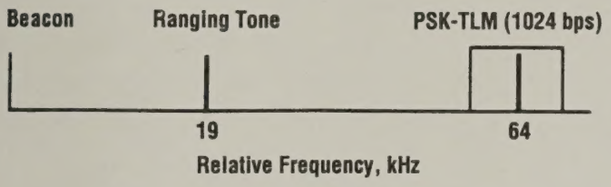


Relative Frequency With Respect to the Beacon (kHz)	Attenuation With Respect to the Beacon (dB)
±19.03687	-8.33
±38.00049	-25.5
±64.08691	-15.73
0.0 (beacon)	0.0 (beacon)

SIGNAL CHARACTERISTICS, CASE 3a OF TABLE 2

f_1 = 19.0 kHz (ranging subcarrier modulated by 35.4-Hz square wave)
f_2 = 64 kHz (PSK carrier)
R_d = 1024 bps (PSK data rate)
$\beta_1 = \beta_2 = 0.79$





Relative Frequency With Respect to the Beacon (kHz)	Attenuation With Respect to the Beacon (dB)
±18.71948	-7.39
±19.28101	-8.90
±38.00049	-15.9
±64.08691	-17.9
0.0 (beacon)	0.0 (beacon)

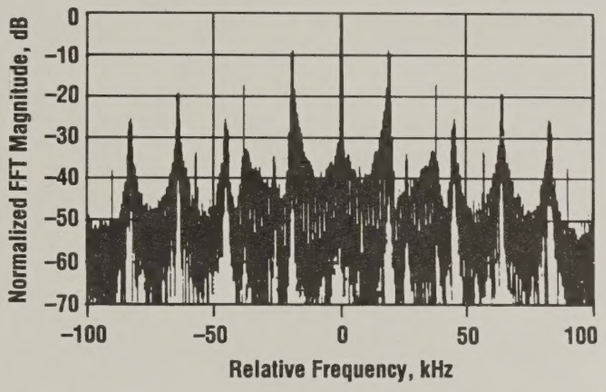


Figure 8. Baseband spectral characteristics of Case 3b.

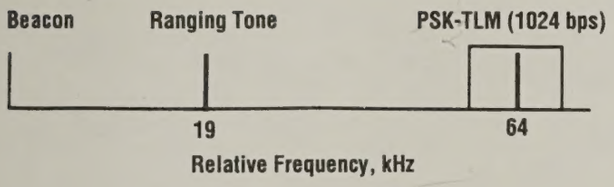
SIGNAL CHARACTERISTICS, CASE 3b OF TABLE 2

f_1 = 19.0 kHz (ranging subcarrier modulated by 283.4-Hz square wave)

f_2 = 64 kHz (PSK carrier)

R_d = 1024 bps (PSK data rate)

$\beta_1 = \beta_2 = 0.79$



Relative Frequency With Respect to the Beacon (kHz)	Attenuation With Respect to the Beacon (dB)
± 7.09229	-18.6
±15.03296	-7.6
±64.0869	-15.8
0.0 (beacon)	0.0 (beacon)

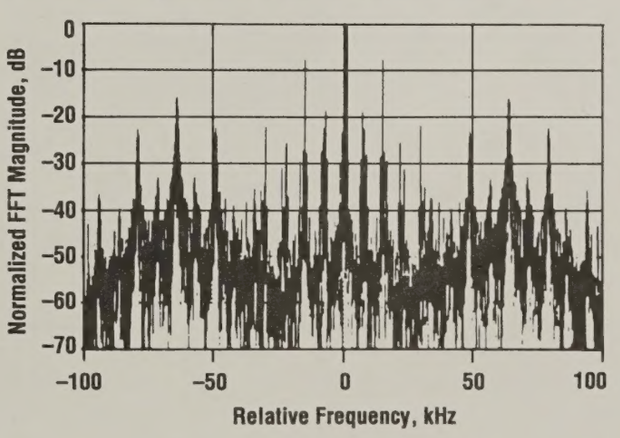


Figure 9. Baseband spectral characteristics of Case 3c.

SIGNAL CHARACTERISTICS, CASE 3c OF TABLE 2

f_1 = 19.0 kHz (ranging subcarrier modulated by 3968-Hz square wave)

f_2 = 64 kHz (PSK carrier)

R_d = 1024 bps (PSK data rate)

$\beta_1 = \beta_2 = 0.79$

sults presented here were compared to the experimental results shown in [7] for Cases 1 and 2. The comparison demonstrated a good match between the predicted simulation results and the measured experimental results.

Conclusion

Spectral analysis of the ACTS downlink beacon frequency (20 GHz) has been carried out and the baseband spectra have been plotted to identify locations and powers of the unwanted components relative to the location and power of the beacon.

The results obtained will help ACTS propagation receive terminal designers and experimenters know *a priori* the locations of these unwanted spikes so that appropriate measures can be taken to avoid a false lock while trying to track the beacon during initial search or acquisition after a prolonged deep fade.

References

[1] F. M. Naderi and S. J. Campanella, "NASA's Advanced Communications Technology Satellite (ACTS)," *AIAA Proceedings*, paper no. 88-0797, pp. 204–224, 1988.

[2] F. Gargione, "ACTS Spacecraft Beacon Characteristics," *Proceedings of the First ACTS Propagation Workshop*, Santa Monica, California, November 28–29, 1989.

[3] P. F. Panter, *Modulation Noise and Spectral Analysis*, McGraw-Hill Book Co., 1965.

[4] K. T. Lin, "Problems of the Beacon Spectra Produced by the GE Telemetry Simulator," COMSAT Labs memorandum, ACTS-NGS-90-052, July 25, 1990.

[5] Signal Processing Worksystem Software, Comdisco Systems, Inc., Foster City, California.

[6] A. Oppenheim and R. Schafer, *Discrete-Time Signal Processing*, Prentice Hall, 1989.

[7] F. Gargione, "ACTS Beacon Measurement Data," *Proceedings of the NAPEX XV*, London, Ontario, Canada, June 1991.

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